Combining information flow and physics-of-failure in mechatronic products

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op woensdag 18 april 2007 om 16.00 uur

doort

Clément Albert Anne Magniez

geboren te Parijs, Frankrijk
Dit proefschrift is goedgekeurd door de promotoren:

prof.dr.ir. A.C. Brombacher
en
prof.dr.ir. M.J.W. Schouten

Copromotor:
dr.ir. J.L. Rouvoye
Acknowledgement

Sometimes, a thesis is seen from the “outside world” as a work carried-out by a lonely researcher confined in his laboratory and/or lost in his books. This, to my mind, is a wrong vision. Although there are indeed some solitary phases in the course of a research, such a work cannot however be achieved without the contribution, the support and the help of different people. I would like to use this opportunity to thank those who have, in one way or another, contributed to this work.

I would first like to express my gratitude to my supervisors, Professor Aarnout Brombacher and Professor Jeu Schouten, who gave me the opportunity to conduct this research at the Technical University of Eindhoven. I sincerely appreciated to work under their guidance, which has been of a great help to achieve this study. They taught me the methodology to conduct a research, shared at numerous occasions their astonishing scientific knowledge in their respective field of expertise, and their ongoing enthusiasm fostered my motivation all along this period. Their critical comments and suggestions on this thesis have obviously improved the quality of my work. In this respect, I would also like to thank Jan Rouvroye, Martin Newby, Dik Schipper, Fred van Houten, Russell Simpson and Steve Perez, the members of my committee, for having read and provided useful comments on this thesis.

This research would not have been possible without my industrial partner, who has been directly involved in this research project. Therefore, I would like to convey my appreciation to Steve Perez and Ton van den Borne who give me the chance to complete my PhD within their organization. They allowed me also to benefit from direct and fruitful contact with industry, which gave a great value to this work. This cooperation allowed me to analyze the research problem from an academic perspective and apply it in an industrial context. I also want to thank Peter Bloemen, Yvonne Groot, Pierre Hendriks, Bart Hovens, Ludwig Nooyens, Len Schoordijk, Bruce Thayer and Ton Wijnen.

My special thanks go to Jan Rouvroye who kindly accepted to be my co-promoter, reviewed in detail my thesis, provided pertinent comments that contributed to improve the quality of this thesis and, finally, polished my writing in English.

I would also like to thank my colleagues from the quality and reliability engineering department at the Technical University of Eindhoven.

I am grateful to my family for their continuous encouragement, patience and support. I must thank my sister in particular whose novice eye in the field of quality engineering, eventually allowed to improve more than just the English.
Finally, I would like to thank all the friends that I have met in Eindhoven, in particular Ludwig and Mascha, who made my integration in the Netherlands much easier. Our discussions about the Dutch and the French culture were always very interesting and endless.
Summary

A continuous acceleration in the rate of technological development, shorter product life cycles, more intense competition due to maturing of markets and globalization, have forced firms to increasingly rely on new products for sales and profitability. However, reliability and quality management becomes extremely difficult and challenging in such circumstances, as products have to be on the market before the manufacturer knows and is able to control their long-term behavior.

Despite the many efforts to predict reliability in the course of the product development process, it is not unlikely to see deviation between predicted and real product performance in the field. Therefore, companies need to react proactively to such deviations. Doing so implies the development of field feedback control loops, which measure field reliability and provide enough information for both corrective actions in existing products and preventive actions in future products. Such a development of reliability field feedback control loop requires, however, considerable efforts for improving existing field feedback systems, since those systems are traditionally focused on logistics of product repair. The difficulty is that failures of complex products are strongly influenced by the product-user interaction. In such a context, the field information should not anymore solely focus on parts/components failures but also on the user-product interaction.

First, a literature review on field feedback systems, reliability and quality of information was conducted. This literature review enabled to establish a set of criteria which field feedback information should fulfill, namely: time, deployment, format and content. As a second step the design and definition of an analysis system for reliability-oriented field feedback information has been carried out.

Once the criteria mentioned above had been established, a case study was performed to assess the quality of the existing field feedback process in an innovative company, in relation to certain products available on the market. Using the developed system, this case study identified the different classes of failures per product, using the classification defined in the roller-coaster model (i.e. class one: infant mortality; class two: early wear-out; class three: random; class four: wear-out). It was found that some products experienced a dominant number of class one and class two failures, while other products experienced none of these failures without the producer realizing. These failures were, despite their importance for the company, not taken into account for quality improvement. Class one failures are traditionally tackled through the implementation of adequate quality control on manufacturing processes and have therefore not been subject to a specific analysis in the course of this thesis. Class two failures concern a distinct sub-population of products showing an accelerated degradation in performance, caused either by product variability (usually internal flaw caused by manufacturing process) or by customer use variability (customer using the product in extreme/unexpected conditions). To prevent reoccurrence of these failures, the design needs to be revised.
Pursuant to this case study, it was noticed that the field feedback information was relevant but not, per se, suitable for root-cause analysis and could not, in itself, allow design improvement. A method for bridging the gap between the available field feedback information and the information actually needed for design improvement was therefore necessary.

From a theoretical perspective, the problem should be tackled using a synthesis of two existing fields of reliability engineering: system engineering and physics-of-failure. The system engineering approach aims at understanding the behavior of and interaction among systems components. The physics-of-failure is a discipline that focuses on the understanding of the physical processes of failure at a detailed level (i.e. component level). This method is suited for analyzing a failure mechanism and improving the design but is far more complex once applied to a complete product because of the too many potential failure mechanisms to be studied. A new method was therefore suggested consisting in the combination of field feedback information (Top–down approach) and physics-of-failure (Bottom-up approach). The physics-of-failure provides analytical models, which explain individual failure mechanisms. The field feedback information, in particular analysis of failed product, also provides significant clues to guide the identification of the relevant system components and the selection of the most likely failure mechanisms to be studied.

Application of the first step of the method resulted, as was expected, not to unambiguous identification of dominant failure mechanisms, but gave, as was the intention, a clear first priority. Subsequent experiments were then performed to confirm, validate or reject the occurrence of this failure mechanism. Parameters were selected, based on product knowledge, comparative study with other products, and correlation between design and potential failure mechanism. As a next step the experiments executed under controlled conditions were compared, on effect level, to dominant field failures. Such iterative process was carried out until a correlation with field failed products could be established. Finally, once the failure mechanism was properly identified and understood, the design optimization phase was undertaken.

The method was applied successfully, and demonstrated that design improvement should be prioritized according to the class of failure occurring on products available on the market. In particular, class two failures can be analyzed and reproduced at design level, so that it is possible to predict failure and adequate design modifications can be suggested. In this study, the method has been implemented on “low medium capital industry and consumers” products that present certain characteristics. However, it is expected that the method could be applied to different products and industries under certain conditions.
Samenvatting

De steeds toenemende snelheid van technologische ontwikkeling, de steeds korter wordende product levenscycels, intensiverende concurrentie en globalisering hebben ertoe geleid dat bedrijven meer en meer afhankelijk worden van verkoop en winst van innovatieve producten. Het goed managen van kwaliteit en bedrijfszekerheid wordt in dergelijke omstandigheden echter steeds moeilijker, omdat producten al op de markt moeten komen voordat de fabrikanten het lange termijn gedrag kennen en kunnen beheersen.

Ondanks veel inspanningen om de bedrijfszekerheid al gedurende het product ontwikkelproces te voorspellen, is het zeker niet onmogelijk dat het voorspelde productgedrag afwijkt van in het veld waargenomen gedrag. Daarom zullen bedrijven, bij voorkeur pro-actief, moeten reageren op dergelijke afwijkingen. Dat vereist de ontwikkeling van adequate feedback systemen die bedrijfszekerheid in het veld meten en voldoende informatie genereren voor correctieve acties in bestaande en preventieve acties in toekomstige producten. De ontwikkeling van een dergelijk feedback systeem op basis van de bestaande systemen vergt echter behoorlijke inspanningen, omdat de bestaande systemen zich traditioneel richten op de logistiek van product reparaties. Het probleem hierbij is dat falen van complexe producten vaak sterk beïnvloed wordt door de product-gebruiker interacties. In deze context zou het feedback systeem zich niet alleen, zoals gebruikelijk, moeten richten op het falen van onderdelen/componenten, maar ook de product-gebruiker interactie hierin mee moeten nemen.

Allereerst is een literatuuronderzoek gedaan, gericht naar veld feedback systemen en naar kwaliteit en betrouwbaarheid van de daarin opgeslagen informatie. Dit heeft geleid tot een set van criteria voor veld feedback, namelijk: tijd, dissimilatie, format en inhoud. Als tweede stap is een systeem opgezet voor het analyseren van gebruiksgerelateerde feedback informatie uit het veld.

Vervolgens, is een case studie uitgevoerd in een innovatief bedrijf met als doel de kwaliteit van het bestaande veld feedback proces met betrekking tot enkele op de markt beschikbare producten te bepalen. Deze studie identificeerde, met behulp van het eerder ontwikkelde analyse systeem verschillende classes van fouten per product, gebruik makend van de klassificatie zoals gedefinieerd in het rollercoaster model (klasse één: kinderziektes, klasse twee: vervoegde slijtage, klasse drie: random fouten, klasse vier: slijtage). Fouten van klasse één en twee bleken dominant in sommige producten en afwezig in ander producten, zonder dat de producent hiervan op de hoogte was. Deze fouten werden dan ook, ondanks het grote belang voor het bedrijf, niet in kwaliteitsverbetering meegenomen. De meer traditionele fouten van klasse één worden gewoonlijk aangepakt door middel van de implementatie van geschikte kwaliteitscontrole in het productieproces en zijn daarom in het kader van dit proefschrift niet verder onderzocht. Fouten van klasse twee hebben betrekking op een afzonderlijke subpopulatie van producten die een versnelde degradatie in productprestatie laten zien, veroorzaakt of door product variabiliteit (gewoonlijk een intern gebrek als gevolg van het
productieproces) of door variabiliteit in klantgebruik (productgebruik in extreme en/of onverwachte condities). Om herhaling van deze fouten te voorkomen, zal het productontwerp moeten worden aangepast.

Uitvloeiend uit deze case studie werd het duidelijk dat de veld feedback informatie relevant, maar niet persé voldoende was voor 'root cause' analyse en dat deze informatie op zichzelf niet voldoende was voor verbetering van het productontwerp. Een methode om het gat te overbruggen tussen de beschikbare veld feedback informatie en de informatie benodigd voor verbetering van het productontwerp is daarom gewenst.

Uit theoretisch perspectief zou dit probleem aangepakt moeten worden door een (nieuwe) synthese van twee reeds langer bestaande disciplines binnen de bedrijfszekerheidanalyse: 'systems engineering' en 'physics-of-failure'. De 'systems engineering' discipline probeert het gedrag van een systeem te voorspellen door middel van het begrijpen van de gedrag van en de interactie tussen systeemcomponenten. De 'physics-of-failure' discipline concentreert zich op het begrijpen van de fysische processen van falen op een detail (componenten) niveau. Deze methode is daarom geschikt voor analyse en verbetering van het ontwerp, maar is erg complex indien toegepast op een heel product vanwege het te grote aantal te analyseren potentiële faalmechanismen. Daarom wordt een nieuwe methode voorgesteld bestaande uit een combinatie van veld feedback informatie ('top-down') en 'physics-of-failure' ('bottom-up'). De 'physics-of-failure' methode levert analytische modellen die individuele faalmechanismen kunnen verklaren. De veld feedback informatie, in het bijzonder de analyse van gefaalde producten, levert belangrijke aanwijzingen die leiden tot de identificatie van de relevante systeem componenten en selectie van de meest waarschijnlijke faalmechanismen die bestudeerd moeten worden.

Toepassing van de eerste stap van de methode leidde, zoals verwacht, niet tot een éénduidig faalmechanisme maar gaf wel een zeer duidelijke prioritering. Vervolgens werden experimenten uitgevoerd om het optreden van faalmechanismen te valideren of te verwerven. Parameters werden geselecteerd gebaseerd op basis van productkennis, een vergelijkingsstudie met ander producten en de correlatie tussen ontwerp en potentieel faalmechanisme. De experimenten, uitgevoerd onder gecontroleerde condities, werden, op effect niveau, vergeleken met dominante veldfouten. Dit iteratieve proces werd uitgevoerd totdat de correlatie met de gefaalde producten uit het veld bewezen was. Uiteindelijk nadat het faalmechanisme duidelijk geïdentificeerd en verklaard was, kon de ontwerpoptimalisatie plaatsvinden.

De methode is succesvol toegepast, en laat zien dat ontwerpverbeteringen op prioriteit gerangschikt kunnen worden overeenstemmend met de klasse van fouten die optraden bij producten in het veld. In het bijzonder fouten van klasse twee kunnen geanalyseerd en gereduceerd worden op ontwerp niveau, zodat het mogelijk wordt om falen te voorspellen en geschikte ontwerp wijzigingen voor te stellen. In deze studie is de methode geïmplementeerd voor 'low medium capital industry and consumers' type producten met bepaalde karakteristieken. De verwachting is echter dat de methode onder voorwaarden ook geschikt (te maken) is voor andere producten en industrieën.
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Chapter One: Introduction

1.1 The need for reliability improvement

Over the last decades, the environment in which business is conducted, especially in the innovative consumer product industry, has changed dramatically. In their attempt to maintain their position on the market and make profit, companies have to be first to enter the market with products that have state of the art functionality, high quality standards at a competitive price [Stalk & Hout 1990], [Smith & Reinertsen 1998]. These trends in the industry have a tremendous effect on the product development process and achieving product quality and reliability targets for new products under these circumstances is increasingly difficult [Den Ouden 2006]. The reasons are that industry has to deal with an increasing complexity of the products, an increasing customer demand in terms of reliability, a reduction in the product development cycle time, and an increasing globalization of the product development process, the market, the competition, and the information (whether in company to customer, or company to supplier relationship).

The increasing product complexity in terms of functionality leads to more difficult prediction on user-product and product-product interactions (interface) [Brombacher 1999]. In terms of reliability, the consequence is unanticipated product failure, which might lead to a customer complaint. In the meantime, in an attempt to reduce time required to bring a product to market, the phase in the course of which product performance is tested is sometimes reduced. As verification and validation tests, however, remain the main sources of reliable data on product performance for companies, neglecting such test phase means that potential risks may be overlooked and as a consequence immature products may be put on the market [Ulrich & Eppinger 2004].

At the same time, the customer expectations as regards quality are high. A company image can be strongly affected in case quality expectations of a product are not met. In addition, most companies adopt an after-sale service policy, which contributes to the quasi-systematic “replace instead of repair” whenever a customer experiences a problem with the product. Such policy has two effects. Firstly poor quality will lead to excessive costs. Secondly the replacement without repair leads to a loss of information with regards to product reliability, as no further analysis is conducted to determine the root-cause of the customer complaint.

Academic research, in collaboration with industries, has been developing many tools and methods aimed at managing quality and reliability (Control chart, Quality Function Deployment, Total Quality Management, Design of experiments, etc). Large improvements in business performance due to the use of such tools have been reported in literature [Bhote 2000], [Schippers 2000]. However, their efficiency is proved only when very detailed and thorough information as well as precise customer specifications are available. Thus, in the context described above, recent research has shown the limitation of their applicability [Den Ouden 2005].
In this turbulent environment, the product development process is entailed with a large uncertainty emerging from the technology and the market, which need to be managed iteratively and proactively \cite{Ganesh2005}. Organizations need quality information to cope with environmental uncertainty and improve their decision-making. It was indeed observed by \cite{Lu2001}, that product quality and reliability problems are often caused by lack of quality information or insufficient information deployment. Furthermore the globalization of business processes will not ease the communication and information deployment process.

Consequently it seems interesting to explore how information is effectively used as a support to improve product reliability and to a larger extent as a learning cycle process. Since the research is dealing with flow of information on quality and reliability, it is interesting to make a parallel with organizational information processing theory. Such theory identifies three important concepts: information processing needs, information processing capability, and the fit between the two to obtain optimal performance \cite{Premkumar2005}. The same structure can be used in this study. First the information needs for reliability purposes should be defined. Secondly the capability of the organization to process the information should be analyzed. Thirdly the gap between the existing situation and the desired situation should be identified to suggest an adequate solution.

For the information processing needs, two aspects should be considered: how can the relevant information towards quality and reliability be obtained and what should be the content of such information.

Early quality related initiatives focused on reducing process variability in manufacturing, later efforts focused on re-engineering the upstream activities of product design and development, where the opportunity to influence the cost and lead time of new products is greatest. However, one often neglected aspect is the learning process using field feedback information. It is anticipated that, for strongly innovative products used in complex field environments, there is a strong likelihood that problems appear in the field, so that is necessary to assess product reliability based on field data \cite{Jones1997}, \cite{Brombacher2005}. It is only recently that companies initiated development of communication channels to get information from the field. Field feedback information can be divided in two types: statistical information and engineering information \cite{Petkova2003}. For the purpose of quality and reliability improvement, engineering information is more relevant than the use of statistical information. If a company wants to improve the quality of its products, it should first and in particular look for the root cause of product failures. Doing so requires the building up of a closed-loop feedback process where a relationship between the customer (i.e. the person who experiences problems) and the specialist from the company (i.e. the person who has knowledge over the product) should be reinforced.
In the light of the foregoing, the first part of this thesis will establish a set of criteria to define the required field feedback information for design improvement. The criteria are chosen on the basis of reliability, field feedback system and quality of information literature review.

Secondly, in a case study, the information effectively collected by a company with regards to quality and reliability of the products is assessed at the light of the criteria previously established.

Finally, once the need and the assessment are compared, a method for improvement can be elaborated and conducted. As earlier research already demonstrated that the major fractions of the causes of reliability problems are unknown and unanticipated [Brombacher1994], it is relatively clear that further analyses for root cause analysis will be required. In this perspective, an interesting approach is to combine physics-of-failure model development with feedback information from the field. It is also a promising approach for characterizing and resolving failure mechanisms in strongly innovative companies. The failures, observed in the field, are reproduced at the design level in controlled conditions in order to understand the failure mechanism. Once the correlation between reproduced failures and field failure is established, a design solution to avoid the reoccurrence of failures can be suggested. To this purpose, the traditional quality and reliability tools should provide good support for selecting parameters, running experiments and analyzing data. By doing so a complete learning cycle is indeed achieved.

The research is carried out with an industrial partner specialized in the copier-printer industry. The products that have been studied in this thesis are classified as “low medium capital industry and consumer” products.

1.2 Thesis overview

This thesis aims at using reliability-oriented field feedback information for product design improvement. For this purpose, the following steps have been performed.

Chapter Two: Trends in innovative industry

This chapter presents the different trends observed in innovative industry and the difficulties that arise in such a context to predict quality and reliability.

Chapter Three: The problem statement

As a consequence, it becomes more difficult to anticipate and analyze every potential failure during product development. Therefore slippage of failures from the design process into the field will become increasingly likely. Since it is not likely that every potential field issue will be captured during product development an efficient field feedback process should be in place to find and react to the unanticipated deviations in product performance.
Chapter Four: Research methodology

The research questions derived from the problem statement are given, and the different methodologies used to answer to these questions are presented.

Chapter Five: The use of reliability-oriented field feedback information for product design improvement

For product design improvement, the reliability-oriented field feedback information should be of a certain quality that is defined in the present thesis. Then a case study is carried out to assess the existing reliability-oriented field feedback information. This case study outlines that the existing information enables design improvement prioritization, but it does not always allow root-cause analysis. For this purpose, a new method is suggested to bridge the gap between the available information and the needed information for design improvement.

Chapter Six: The analysis of individual field failures

The method is applied to one sub-system of the xerographic process. The sub-system is described in terms of physical model and its associated conceptual failure mode so that failures observed in the field could be explained. In parallel, the analysis of the field failed products is carried out

Chapter Seven: The use of guided experiments to reproduce field failure and to enable root-cause analysis

Experiments are run to confirm or rejected hypothetical failure mechanisms derived from the combination of field feedback information (top down) and physical model (bottom-up) until the reproducibility with the field failures and the root-cause analysis is achieved.

Chapter Eight: The improvement of the product design

Some design modifications are suggested to prevent the reoccurrence of the failure. Early risk prediction is demonstrated on a new sub-system design.

Chapter Nine: Conclusion and recommendations for further researches

This chapter summarizes the conclusions, discusses generalization and gives recommendations for further researches.
Chapter Two: Trends in innovative industry

The aim of the present chapter is to introduce the trends observed in innovative industries, and the impact these trends have on quality and reliability management. Due to the strong competition between companies sharing the same market, companies need to optimize performance, price and delivery. These conflicting requirements lead to changes in product development processes and consequently on the management of quality and reliability.

2.1 Introduction

Nowadays, as competition between companies sharing the same market is growing stronger, it becomes necessary for a company to differentiate its products from products of its competitors. This context gives an incentive to provide to their customers a product with a high functionality and a better service at an attractive price. Another non-negligible constraint is the tremendous pressure on time to market, which necessitates reducing project lead time. These new requirements put pressure on the business process and their impact on product quality and reliability is set forth in the following chapter. As a result of such requirements, new demands are also expressed by these companies to tackle quality and reliability. These trends are observed in industry that produces “low medium capital industry and consumer” products as studied in the present thesis.

2.2 The increase in product complexity

In order to satisfy customers and remain competitive, companies endeavor to deliver products with new functionalities, with the effect that products are more and more complex. Implementation of new functionalities may notably be due to:

- A redefinition of the product, in accordance with customers’ expectations, which explicitly requires the introduction of such functionalities. These modifications are captured via surveys often conducted by the marketing team, and known in literature as the “Voice of Customer”.
- The company itself introduces new functionalities even if the customer did not specifically require, e.g. with a view to improve current product performance or to reduce costs.
- A strategy choice: existing literature on competitive strategy stresses the importance of strategic innovation as a crucial means to create competitive advantage [Johnston&Douglas03].
Finally, in other cases, a company may decide to bring a new functionality on the product just because competitors have already introduced it, so that not including it may cause loss of customers.

However, this tendency will not ease the prediction of quality and reliability problems, as it necessarily implies additional interfaces: (i) internal to product (subsystems level) (ii) product-user (iii) product-product (interfacing, connections). Therefore, quality problem analysis becomes much more complex: there are much more functions and features to check. In addition, as reliability problems in new products are partly caused by customer’s behavior, and as the way a customer will handle new functionalities is unknown, this adds uncertainty with regard to reliability. More interactions between parts or modules lead to an increase in potential failure mechanisms.

In addition to the successful integration of new technology, companies also need to become increasingly effective in sharing knowledge in multi-disciplinary teams. Product development processes involve the combined inputs of specialists representing a wide range of engineering disciplines. These engineers need to communicate and interact with other departments such as repair organization, logistics, or purchasing. Recent studies addressed the issue of development, use and sharing of knowledge for problem solving in a multi-disciplinary team. Such studies indicate that these teams encounter a number of difficulties while working on complex problems [Boshuizen&Tabachnek-Schijf1998] [Vennix1998]: (i) dissimilarities of problem representations between team members (ii) preference for a single perspective of a problem (iii) vagueness about how much knowledge needs to be shared (iv) lack of common goals between individuals about individual tasks and the common goal of the team.

In conclusion, quality and reliability management requires the optimization of technology use and efficient knowledge sharing in collaborative multi-disciplinary teams.

2.3 Outsourcing, globalization and segmentation of business processes and products

Nowadays, companies compete on a global market and therefore companies need to optimize their performance on a global scale. In the meantime, due to the increase in product complexity, a higher specialization is necessary. For this purpose, companies have favored the practices of increased “outsourcing” or the process of seeking external sources of supply as compared to the completion of work within the company. This, combined with the current emphasis on globalization, has resulted in suppliers being selected from many different geographical centers located throughout the world.

In this context, effective integration of suppliers into the product value/supply chain will be a key factor for manufacturers to achieve the improvement that is necessary to remain competitive [NazliWasti&Liker1997]. It is also demonstrated in the studies from [Ragatz1997] that in depth and early integrations are necessary to reduce cycle times, improve quality and reduce costs.
Business processes become increasingly complex due to the globalization and outsourcing of development activities. In this environment, the main threat, in terms of quality and reliability, is the bad deployment of information, the loss of information or delay in obtaining the information due to worldwide spread activities. Once again, collaboration between outsourcer and supplier is successful only if a well-structured cooperation is ensured. Besides on the long term, outsourcing may lead to a possible loss of knowledge and high dependency upon the supplier.

2.4 The change in business model

When time-to-market goals are achieved, the benefits include (i) product name recognition, (ii) ability to set industry standard, (iii) recognition as a leader, (iv) expansion of customer base, and (v) maximization of profits [Levin&Kalal2003]. However, such objectives cannot be met without changing the product development process [Clark&Wheelwright1995]. In order to minimize the time that it takes from the identification of needs to the ultimate delivery of the product, several activities of the product development process are executed on a concurrent basis (concurrent engineering). Another alternative is to shorten different activities. To do so, companies will sometimes reduce time-consuming activities such as testing [Petkova2003]. As in the meantime, the increasing complexity of products requires longer and complex tests, it is expected that potential reliability problems be overlooked. If companies want to avoid pitfalls with reliability and quality under these circumstances, the problems should be identified as early as possible during the product development process, in a phase of maximal flexibility, where design changes cause minimal delay and costs [Minderhoud1999].

2.5 The increase in customer requirements

[Goldhar1991] described how customers are becoming increasingly more sophisticated and are demanding customized products and services that are more closely targeted to their needs. Among these needs, customers expect products with high quality standards. Quality is not any more considered as “nice to have” but is a prerequisite to fulfill customer requirements. Moreover, customers are encouraged by manufacturers to bring claims whenever they are dissatisfied with products. Customers not only have the right to complain but also to get their money back if problems occur within legal (and sometimes contractual) warranty periods. According to [Murthy2002], warranty is an element of new product marketing because better warranty is a signal of product quality in the eyes of customers. Post sales factors like warranty, service and maintenance are considered by customers when they choose a product [Lele1983]. In the meantime, duration of this warranty period has been, in most industries, largely extended, so that it is easily understood that poor quality will contribute to excessive costs for the manufacturer.
2.6 The transition from “manufacturing industry” to “service industry”

The continuous influx of new technology renders more and more difficult the support on products/systems since it requires special knowledge about the product and its technology. As a consequence, the management literature suggests that product manufacturers should integrate service (“industrial service” or “product-related services”) into their core product offerings [Wise&Baumgartner1999]. Such an initiative is particularly beneficial for durable manufactured products since these products usually require services as they advance through their life cycle (acquisition, installation, operation, upgrades, decommission, etc.) and have an associated cost of ownership beyond the purchase price (spare parts, consumables, maintenance, etc.). However, [Oliva&Kallenberg2003] underline that this kind of service policy usually leads to support maintenance contract (i.e. fixed prices covering all services over an agreed period) and that profitability under this pricing mechanism depends on how accurate the organization is in assessing the risk of failure for the product. As a consequence, the manufacturer needs adequate information to optimize the risk prediction. Such a transition is already effective in the copier-printer industry. [Oliva&Kallenberg2003] stress that “firms such as –computers, electronics, autos- are looking into services as a way to differentiate their offering, satisfy their customers and improve their financial performance”.

2.7 Conclusion

This introduction highlights two conflicting trends. Reliability and quality requirements are very high, whereas the product complexity makes the predictability on product performance even harder. While the information on product reliability is obtained relatively late in the product development, companies would like to be provided with appropriate information as early as possible so as to anticipate risk. This conflict of trends sets the requirements for managing reliability in the current context that is discussed in the next chapter.
Chapter Three: The problem statement

The trends presented in chapter two induce risks and uncertainties that should be managed in the course of the product life cycle. In such conditions, reliability prediction becomes extremely difficult, so that careful field product performance monitoring is necessary. Doing so requires reliable information and excellent information processing in order to achieve a complete learning cycle.

3.1 Introduction

Because of intensifying international competition, companies are seeking ways to gain a sustainable advantage in the market place. To ensure economic competitiveness regarding their product, engineering must be closely associated with economics and economic feasibility. This is best accomplished through a system’s life cycle approach that is described in section 3.2.

However, to limit the scope of this thesis, the emphasis of this research is about the need for companies to manage properly quality and reliability with regards to their products in order to optimize the product life cycle. In the context of this thesis, a certain definition of the product life cycle is used and is consequently defined. Then, quality and reliability are also defined. Then, more attention is given to the activities related to the management of quality and reliability carried out during the product development process. Nevertheless, companies experience difficulties to assess risk associated to technology and/or market during the product development process. As a final consequence, some potential reliability problems can be overlooked, and field observations may strongly deviate from prediction. As the actual product performance is determined by its interaction with customers, managing reliability and quality among others implies to capture field product information for analysis and finally improvement. These aspects are covered in section 3.3.

Such an approach requires an adequate management of risk in a business context that is covered in section 3.4. Then, the importance of information flow as an enabler for managing risk, uncertainty, quality and reliability will be highlighted in section 3.5. Finally, the notion of control-loop for a business process will be introduced in section 3.6. However, as it will be shown the implementation of control-loop for activities that are undertaken out the product development is not yet a common practice and will be the main focus on this thesis.
3.2 A system’s life cycle: a definition

The system engineering challenge is to bring products and systems into being that meet customer expectations cost-effectively. For this purpose, literature indicates that properly and functioning engineering systems require the application of an integrated life-cycle oriented systems approach [Blanchard&Fabrycky1998] [Immonen&Saaksvuori2005]. Life-cycle engineering goes beyond the life of the product itself. It is simultaneously concerned with the parallel life of the manufacturing process and of the product service system (Figure 3.1).

The life cycle of a product or system begins with the identification of a need. It subsequently extends through conceptual, preliminary and detailed design, as well as production, customer use, phase-out and disposal. The principal behind life-cycle engineering is that the entire life of the product should be considered in its original design. An engineering design should not only transform a need into an idea that produces the desired product, but should ensure the design’s compatibility with related physical and functional requirements during manufacturing and operation. This includes taking into account the life of the product (as measured by its performance), reliability, and maintainability.

In essence, there are actually three coordinated life cycles going on at the same time. These parallel life cycles are initiated when the need for the product is first recognized. During conceptual design, it follows that consideration should simultaneously be given to the product’s manufacturing. This begins the second life cycle, i.e., the creation of a manufacturing process including production planning, plant layout, equipment selection, process planning, and other similar activities. The third life cycle should also be initiated at the preliminary design phase. It involves the maintenance and logistic support activities needed to service the product during use and to support the manufacturing capability during its duty cycle. Therefore, the performance of a product depends not only on its design and operation but also on the servicing and maintenance of its item during its operational lifetime.

**Figure 3.1: Product, manufacturing, and support life cycles [Blanchard&Fabrycky1998].**
In this thesis, the management of reliability in the course of the product life cycle is mainly considered. However, reliability issues might have some consequences either on manufacturing activities or on service activities. In particular, as it will be shown later in the thesis, the interaction with the service organization plays a significant role in the management of reliability.

3.3 The management of reliability in a product’s life cycle

This thesis focuses on the management of reliability in the course of a product’s life cycle as defined in Figure 3.2. This definition of a product’s life cycle will be used in the remainder of this thesis. At each stage of the product life cycle, still more reliability-related information may be obtained so that updated reliability assessments are made periodically as appropriate. Since total quality and reliability management means continuous improvement, accurate reliability assessment once the product is in the hands of the customers should also be available. The interest of this approach is to make a distinction between the demonstration of the product reliability carried out in the course of the product development process and the achieved reliability when the product is in the field. In particular, the reliability issues that occur in the field should be correlated to the activities undertaken during the product development process so that a continuous learning process is in place.

![Figure 3.2: A product’s life cycle.](image)

3.3.1 Quality and reliability: some definitions

Customers indeed drive product requirements in terms of quality and reliability. [Hoyer2001] reviewed the different definitions on quality available in literature: the only common aspect among the studied definitions is that quality must be defined in terms of customer satisfaction. However, such a definition remains subjective and does not really address the design aspect, which requires measurable product characteristics. For this purpose, the definition from [Lewis1996] is more adequate since it includes both aspects.
According to [Lewis1996], two criteria must be satisfied to achieve high quality:

- The product design must result in a set of performance characteristics that are highly optimized to customer's desires and needs.
- These performances must not be susceptible to any of the three major causes of performance variability: variability or defects in the manufacturing process, variability in operating environment, deteriorations resulting from aging.

It is often considered that these three causes of variability result in large impact on product reliability. The bathtub reliability model is built upon these causes of variability.

The bathtub reliability model consists of three phases (Figure 3.3):

- Phase 1: early failures due to manufacturing variability
- Phase 2: random failures due to operating environment variability
- Phase 3: wear out failures due to product deterioration

[Lewis1996] defined reliability as follows:

*Reliability is defined as the probability that a system will perform its intended function for a specified period under a given set of conditions.*

When a product/system ceases to perform its intended function, it is considered as failed. Therefore, another way to define reliability is according to [Davis2006]:

*Reliability is failure mode avoidance*
Nonetheless, the given definitions raise all the difficult exercise of quality and reliability management: the product is used by customers, whose perception of a quality-reliability problems might differ from the designer’s point of view. In addition, recent research underlines that customers do not only complain on technical product failure, but also on non-technical failures [DenOuden2006]. In order to take into consideration this difference, [Brombacher et al 2005] distinguishes two classes of quality-reliability problems:

- **Hard reliability-quality problems**: situations where the product is not able to meet both the explicit (technical) product specifications and customer requirements.

- **Soft reliability-quality problems**: situations where in spite of meeting with the explicit product specifications, a customer explicitly complains on the (lack of) functionality of the product.

In this thesis, only hard reliability-quality problems will be considered. From the manufacturer perspective, it is important to understand what the root-cause of the hard failure (i.e. failure mode understanding) is, so that the correct counter-measure is implemented on a revised design to prevent the reoccurrence of the failure.

In order to meet the customer requirements, companies have complete processes in place to develop a product and bring it to the market. It is a cross-functional work, which involves different teams. In order to understand the chain of activities which lead to a product, an overview of the product development process is given.

### 3.3.2 A generic description of the product development process (PDP)

The literature provides several definitions for the notion of product development process (PDP). The Product Development and Management Association defines a PDP as a disciplined and defined set of tasks and steps that describe the normal means by which a company repetitively converts embryonic ideas into saleable products or services [PDMA2006]. Clausing1994 gives a more specified definition of a PDP: a process to develop products through the phases of concept, design and production.

To give further details, a generic description based on [Ulrich&Eppinger2004] is given below. However, one should not forget that the important aspect of the product development process is that it consists in a multi-disciplinary set of activities (marketing, development, production, service and commercial), where exchange of information between teams is a key-factor to success.

Several modifications to the presented generic description might appear due to the complexity of the products, to the development cycle time of the product, to the safety requirements of the product, to the choice of the management organization and so on. However, six steps can generally be distinguished and they are introduced below. In addition, some examples of different tools and methods used to manage quality and reliability during the product development process will be presented. They are mentioned
as examples, and their use is not rigorously limited to one phase of the product development process.

1. The concept phase:

In the concept phase, the strategy and planning for a product are determined. The functional and aesthetic demands and wishes are investigated in detail, the positioning within the product portfolio is determined, as well as the targeted price of the product, and the timing of market introduction. A comparison with competitors is done and the customer requirements are translated into technical requirements. At this stage, several concepts might still be in the mind of the product development team. A risk analysis might help to select some concepts among others.

The process of translating customer needs into a set of specifications may be accomplished by the quality function deployment (QFD) method [Clausing1994]. The foundation of QFD is the belief that products should be designed to reflect customer’s desires and tastes-so marketing people, design engineers and manufacturing staff must work closely together from the time product is conceived [Clark&Wheelwright1995]. QFD is a kind of conceptual map that provides the mean for inter-functional planning and communications.

2. The specification phase:

In order to make the designing of a complex product manageable, a product is usually divided into modules. During the specification phase, specialists build a preliminary design of the different modules and their interfaces.

In this phase, Failure Modes and Effects Analysis (FMEA) can be used. FMEA is a methodology for analyzing potential reliability problems early in the product development process [Creveling2003]. FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate or prevent the failures.

3. The basic design phase:

The first complete product, containing all modules, is developed in the basic design phase. The first prototypes are assembled. During the basic design phase, the functional concepts that determine to a large extent the costs of the products become more or less fixed.

Computational testing (e.g. finite element method) might be used to compare different designs. For large capital equipment/system, they might be used instead of or before the experimental testing phase starts. For the “low-medium capital industry and consumers” products, analysis tests (also called advanced stress testing) are usually carried out for reliability purpose. They intend to highlight the weaknesses in the design by accelerating failure mechanisms. These tests use some increased stresses and harsh environmental conditions. Several kinds of tests exist: (i) highly accelerated tests, (ii) multiple environments over stress tests, (iii) random multiple environment over stress test
They give some first indications on the potential failure modes, the operational limits of the design and the destructive limits of the design.

4. The detailed design phase:

During the detailed design phase, much attention is given to the solution of interaction problems between the different modules. Furthermore, the design is checked on reliability, maintainability and safety. The detailed design phase is aimed at designing the product in such detail that preparations for production can start.

In this phase, verification tests are carried out to estimate the technical life of the product. The design can still be modified to improve reliability performance. In order to make the product more robust and to reduce product variation, the strategy of variability reduction is often employed. Generally three sources of variation are identified: manufacturing variation, environmental/deterioration variation and usage variation. The design might be reworked to counter these sources of variation using design of experiments methods (DOE) [Bhote2000] [Montgomery2005]. DOE enable to determine which factors (product parameters) are most sensitive to variation and which factor levels (parameter values) minimize the variability in the desired performance parameter.

In the mean time, the designer’s objective must be to optimize the product design with the production system. The use of Design for Manufacturability (DFM) practices facilitates this objective [Clark&Wheelwright1993]. It helps in reducing the variations that might arise from the manufacturing process. A number of design guidelines have been established to achieve higher quality, lower cost, improved application of automation and better maintainability. Examples of these guidelines are as follows: reduce the number of parts to minimize the opportunity for a defective part or an assembly error, foolproof the assembly design (poka-yoke), avoid tight tolerances beyond the natural capability of the manufacturing processes, design robustness into products to compensate for uncertainty in the product’s manufacturing, and so forth.

5. The engineering phase:

In the engineering phase, preparations for actual production are made. The production activities and flows are determined, production drawings and procedures are made and administrative and quality control procedures for production are written. A first product is manufactured or, in case of mass production, a pilot run is arranged, to check the effectiveness of the production methods and tools.

6. The production phase:

In the production phase, the production is generally ramped-up gradually. It is also at this time that the capability of the different manufacturing processes is fully assessed.

For this purpose, the manufacturing team uses statistical process control (SPC) and process capability tools. Statistical process control is a set of methods using statistical tools such as mean, variance and others to detect whether the process is under control. Process capability tools measure whether the manufacturing process is able to deliver
product that meet the specifications usually based on customer requirements. It is the last step before shipment to the customer.

3.3.3 The management of reliability in the product development process

In order to optimize the product design during the product development phase, the design team will face among others the following issues:

- Do we have information derived from previous products to correctly assess the risk associated with our design?

Such information is only available if adequate information on the performance of the previous products is available, and the information feedback has been correctly implemented.

- Do we have sufficient information on customer behavior and/or conditions of use to implement representative tests?

The effectiveness of a test is dependent on its ability to simulate properly customer usage. In this phase, the information flow is a dominant factor to achieve successful results. For this purpose, two main sources are usually used. The marketing team usually transmits the “voice of the customer” (VOC), which expresses the customers’ expectations, to the design team. On the basis of the VOC, the design team should draw representative test matrices to screen the product robustness. Secondly, field feedback data is also relevant if experience on previous products shows that several customer profiles have huge impact on product reliability.

- Which design test methodology is the most appropriate to simulate the maximum of potential failures modes from the product?

In this phase, the analysis of failure modes observed on previous or current products is a prerequisite to achieve a positive outcome. Effectively, the failure mechanism and its driving factors should be known to demonstrate design robustness against such failure mechanisms.

- How can we optimize our testing with regards to time constraints?

Several methods are available for gaining time in the testing phase. It is mainly covered by accelerated testing. Accelerated testing is a classical solution for the implementation of tests where product failures need to be activated faster (and cheaper) in a well controlled environment at the early stage of the product development process [Lu2000]. However, such tests are realistic only when the relevant failure mechanism is triggered.

In order to be able to answer accurately to these questions, it seems clear that a correct knowledge on previous products will help to assess risk, to prioritize the different activities, and to use relevant tests. It outlines also that precise information is not sufficient, but that the knowledge on the failure mechanism is required.
3.3.4 The management of reliability in the field

In order to improve the knowledge on the product, the following questions must be addressed:

- **Does the company have a field feedback loop to measure field product performance?**

It is the minimum requirement for a company to compare their reliability prediction with actual product performance.

- **Is the level of information sufficient to distinguish/determine the different failure modes?**

It should be quality and reliability oriented and it should contain the necessary information to map reliability according to different models available in the literature. It could be either some statistical information (lifetime distribution) or some engineering information (failure modes).

- **Can these failure modes be related to the different processes during the product development process?**

At this stage, the information is analyzed so that the failure mechanism is understood and the root-cause is known. If a specific process is involved, corrective-actions to limit or eliminate its influence on the failure should be carried out.

- **Is this information communicated to the relevant actors and used for product quality or reliability improvement?**

The learning cycle is completed and the communication ensures that the continuous improvement is beneficial for all persons involved in the product development process.

3.3.5 Conclusion: the problem statement

Despite, the many efforts to predict reliability in the course of the product development process, it is not unlikely to see deviation between predicted and real product performance in the field. Indeed, the introduction of a new technology or the penetration of new markets often reveals unanticipated customer profiles and/or unexpected weakness/flaws in the technology used. Therefore, companies need to have proactive mechanisms in place to react fast and efficiently to such deviations. Doing so requires the implementation of efficient and effective field feedback control loops. These systems should have the ability to measure actual field reliability and generate rich enough information for both corrective actions in existing products and preventive actions in future products.
For this purpose, companies need:

- To capture the real product reliability that is at the customer in the field,
- To correlate the predicted reliability with field reliability: it is the only way to validate the design activities of the product development process,
- To have an efficient learning cycle so that the factors that influence reliability are identified: engineering design, materials, manufacturing, operations, maintenance and so forth.

To do so, companies rely on quality information and need to implement control-loop systems in their business processes to manage risk in the course of the product life cycle. These notions are explained in the next sections.

### 3.4 Risk management in the product life cycle

Projects rarely proceed exactly according to plans. Some of the deviations from the plan are minor and can be accommodated with little or no impact on project performance. Other deviations can cause major delays, budget overruns, poor product performance, or high manufacturing costs. It is the purpose of risk management to assemble, in advance, a list of what might go wrong. Risk is defined in this context as the potential that something will go wrong as a result of one or a series of events.

In the course of the product development process, potential risks might arise from different domains [Ulrich2000] [Keyser2002]:

- Technology risk: product design, platform development, and manufacturing technology,
- Market risk: consumer and trade acceptance, potential actions from competitors,
- Financial risk: commercial viability,
- Operations risk: internal organization, project team, supply and distribution.

In such conditions, risk has to be managed with an organized method for identifying and measuring risk and for selecting and developing options for handling risk. [Miller2001] distinguishes two broad categories of risk management:

- Decision theoretic approaches that by and large assume that risks are exogenous, probabilistic and partly endogenous,
- Managerial approaches which focus on the front end issues, turbulence, and the shaping of risk drivers.
In an innovative context, high risk products are those that entail unusually large uncertainties related to the technology or to the market so that there is substantial technical or market risk. In this context, [Luitjen2003] provides the most appropriate definition of uncertainty: uncertainty is the operational absence of information (useful experience and/or knowledge) from the past. For this reason, the potential for risk becomes increasingly higher as complexities and new technologies are introduced into the design of new systems [Blanchard&Fabrycky1998]. Consequently, the theoretic approach alone seems unlikely to work out because risk in innovative projects emerges over time and is indeterminate. [Oberkampf2004] underlines that the mathematical approach to tackle uncertainty derived from the lack of knowledge or information is proven to be much more of a challenge. Thus the intellectual exercise in which the complete set of relevant futures can be laid out is difficult to achieve under these conditions.

As a consequence, the managerial approach is required to compensate deficiencies in the theoretical approach. [Keyser2002] emphasizes that risk management is also dependent on the firm’s ability to influence risk factors. However, the list of potential problems becomes rapidly too large for each single problem to be handled. Therefore, product managers have to select and prioritize the actions to be pursued. In order to take the right decision, they rely on an excellent source of information. On the basis of such information, risk is continuously reassessed for unforeseen risk and deviations from the risk management plan. It is the purpose of the next section to give further insight on the notion of information in a business process and on quality of information.

3.5 Information flow in the product life cycle: some definitions and characteristics

A product development process could be described as an information processing system. [Gibson1988] suggests that, when considering an organization as an information-processing system, the heart of the process is information and the objective is that an organization effectively receives, processes, and acts upon information to achieve performance. Therefore, risk can only be managed properly if the quality of information that is used for taking decisions is high.

In literature, several definitions on information quality can be found. [Huang1999] uses the following: “information quality can be defined as information that is fit for use by information consumers”. Such a definition does not explicitly set criteria for information quality. However, it emphasizes the fact that analysis of the information is needed in order to assess the quality of the information. It suggests that proactive management is required if the information is not adequate. [Brien1991] defines information quality as: “The degree to which information has content, form, and time characteristics which give it value to specific end-user”. In Brien’s definition, information quality is more specific although the characteristics have to be customized according to the context of application.
However, it seems important to add other characteristics to the definition from Brien. Cost seems a crucial criterion in a business context since quality is also a relation between cost and benefit. Information deployment also appears to be an important issue since information is useful only if it reaches the relevant people. Depending on the application context, the source of relevant information should also be identified. Thus, in the context of quality and reliability management and in order to facilitate early risk prediction, the quality of the information should be assessed with respect to the following characteristics, based on previous research [Guthenke1999], [Sander1999], [Petkova2003]:

1. **Content**

If new products are developed based on existing technologies, the knowledge of problems that are encountered on current products will provide relevant information. It requires knowledge of the dominant failure mechanisms in these current products.

If new products use evolutionary design principles (new technology consists of extrapolations to-and enhancement of-existing technology), feedback data from the behavior of past products might be used to allow early prediction.

2. **Deployment**

The information deployment should guarantee that the relevant groups get access to the right information they need. A great deal of quality related data is collected throughout the company, but generally these data are acquired by various departments of the company. These departments are not necessarily linked together and there is not always a specific section of the company to coordinate the information flows.

3. **Time**

As far as time is concerned, a general consideration is that the information should rapidly be deployed to ensure that timely actions are taken to solve problems. In the case of the development of derivative products, if the information comes too late, several generations of product will use the same design with the same possible weaknesses. Thus, relevant information should preferably be available before the development of the next generation of product.

4. **Source**

One should not forget that one of the main sources of information on actual product performance is in the field, so that each deviation from prediction should be understood. Furthermore, business processes must continuously be improved, in particular by closing learning cycles. For this reason, it seems a pertinent approach to incorporate such information in the business process.

With the given definitions and criteria, it is clear that information quality depends on the use of the information and on the context of application. In order to provide more insight on the problems encountered with the design of an information quality flow, further
analysis is required. Such analysis will be carried out later in the thesis. It is also underlined that the information should be field product oriented. This implies that the product development process should work as a closed loop system. It seems the most relevant approach to reduce uncertainty, and to prioritize the actions for improvement.

3.6 A business process as a closed-loop control system: a prerequisite for reliability management

3.6.1 Control-loop system: a definition

The analogy between a business process and an engineering device is an excellent way to reveal the role that control-loop systems can play in business processes. Most engineering systems are deployed and then operate in an environment that changes over time. A changing environment can lead to system instabilities unless control action is applied. In a business process case, changing environment can be attributed to: a new technology implementation, a new manufacturing process, a new market, new customers and so on.

There are two basic types of control systems: open-loop control systems or closed-loop control systems. In an open-loop control system, the optimal control action is completely specified at the initial time in the system cycle. In a closed-loop control system, the optimal control action is determined both by the initial conditions and by the current state conditions. Whereas in an open-loop control system, all the decisions are made in advance, in a closed-loop control system, the decisions are revised in the light of the new information received about the system state.

According to the type of product and its associated development cycle time, the implementation of a certain type of control-loop system is more or is less adequate.

For large capital equipment, “everything should be right for the first time” (e.g. nuclear plant, airplanes, bridges…), the product/system is designed and built only once. The business process works essentially in an open-loop control mode. The product development process is generally long (several decades) because of the numerous iterations to make sure that all potential risks are identified. Therefore, the level and the quality of information needed are high, and it requires formal and explicit description of all the internal processes.

The industries that manufacture “low medium capital industry and consumer” products can not follow an approach as conservative as in the large capital equipment. Conservative design margins, such as used in the past, can often no longer be used for reasons of cost-efficiency. If the application of new, immature, technology can create a cost benefit companies will certainly consider this. This combination will often result in products operating in the field close to their limits. Inevitably this can result in unanticipated field failures. Therefore, these industries need to implement efficient field feedback system to find and react to unanticipated deviations in the product performance. In this case, the business process should work in closed-loop control mode.
In order to have a well functioning closed-loop control system, four elements are absolutely required (Figure 3.3):

1. An output, the controlled characteristic or condition of which is measured.

For quality and reliability purpose, the controlled characteristic to be measured is the field product performance.

2. A sensory device that measures output. Information gathered from a sensory device is essential to the operation of a control system.

The different channels/indicators used by companies to retrieve and analyze field feedback should be designed to play this role.

3. A control device that will compare measured performance with planned performance and will determine the need for control action based on the information provided by the sensory device.

Quality and reliability specifications for the product should be clearly grounded so that the product development team is able to compare product deviation with design prediction.

4. An actuating device that will alter the system to bring about a change in the characteristics or conditions being controlled.

This step requires the problem identification, the root-cause analysis and the design change implementation according to the severity of the problem.

![Control system elements and relationship](image-url)
3.6.2 Examples of existing quality and reliability control-loop systems in the product development process

The notion of control loop for processes is already applied for different purposes in the product development processes, especially during development and production.

For example, as mentioned previously, most manufacturing processes are regulated through the implementation of statistical process control and process capability tools. As soon as deviations are observed, the manufacturing team investigates the causes of variations so that corrective actions are undertaken. [Bhote2000] developed a method to find the root-cause of deviations in manufacturing processes.

The Six Sigma DMAIC methodology (Define, Measure, Analysis, Improve and Control) as well as the Deming cycle (Plan, Do, Check, and Act) have been developed to allow process control and continuous process improvement. The Six Sigma DMAIC proceeds as follows:

- Define phase: in this phase, the process improvement goals that are consistent with customer demands and company strategy are defined.

- Measure phase: in this phase, the baseline measurements on current process for future comparison are carried out.

- Analyze phase: in this phase, the relationship between factors and the causality of factors on the process deviations are established.

- Improve phase: in this phase, the process is optimized based upon the analysis using techniques like Design of Experiments

- Control phase: in this phase, some pilot runs are carried out to establish process capability. Some control mechanisms are implemented to ensure that variances are corrected before they result in defects. The variances in the process over time should be report to the proper stakeholders.

3.6.3 Control-loop systems out of the product development process and in the field: a gap

It is however observed that the implementation of closed-loop control systems based on the performance of field products is not yet a common practice [Petkova2003], [DenOuden2006]. [Petkova2003] underlined that the use of field feedback information for product quality and reliability improvement was not possible in the consumer electronics industry.

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As companies need to predict, evaluate, and improve the quality and reliability in the hands of the customers, it seems a valuable approach to develop further research in this direction in another type of industry. In the thesis, the research is carried-out in the copier-printer industry. Copier-printer products could be defined as “low medium capital industry and consumer” products. Their main characteristics are as follows:

- A durable manufactured product with a lifecycle of several years (2-5 years). These products are often under maintenance contract so that all uncontrolled reliability issues lead to high cost for the company,
- A relative high cost of acquisition (from 10 000 euros up to 200 000 euros). Once a reliability-quality issues is experienced with a product, it is very likely that the customer will complain to the manufacturer,
- The products are not used by professional end-users: some important variability in use is expected.
- The products are produced in relative large volume: some potential variability in manufacturing processes is anticipated.

3.7 Conclusion

Industry that develops and manufactures “low medium capital industry and consumers” products will hardly work efficiently without functioning as a control loop system in closed mode. The control loop should be field-oriented to understand why the product did not perform its intended function in the hands of the customers. Such a development of reliability field feedback control loop requires, however, considerable realignment (or even structural redesign) of existing field feedback systems, since those systems are traditionally focused on logistics of product repair [Petkova2003].

Indeed, up to the 1990’s, system reliability engineering considered that three broad classes of failures could occur on engineering devices: early failures, random failures, and wear-out failures. In order to prevent the occurrence of these failures, rigorous testing programs were in place so that early failures were prevented through the implementation of burn-in testing and wear-out failures were avoided thanks to an optimized maintenance policy. As a consequence, the dominant field failures were of a random nature induced by defective components/parts. An accurate follow-up of components/parts performance was adequate to build reliability prediction model based on field data. This approach was sufficient to manage reliability on account of a limited amount of functionalities incorporated into product and a homogenous population of users.

Nowadays, the heterogeneity in products and users, combined with a business process under pressure, leads to a much wider variety of field failures [Brombacher et al 2005]. For this purpose, the four-phase roller coaster model has been developed to take into consideration the emergence of the new classes of failures. In particular, the classes of failure I and II need to be tackled efficiently because they usually lead to high customer
dissatisfaction and to high cost for companies. As a consequence field feedback systems should enable a much more comprehensive analysis of the field issues. Doing so implies the development of a new approach that combines quality analysis (i.e. understanding of product-variability and user-variability) and reliability analysis (i.e. field use of product and failure analysis) out of the product development process and in the field. Traditional quality methods, as developed by [Bothe2000], strongly rely on accessible information within the manufacturing process, precise product specifications and assessment of product quality at time=0. The approach is somehow more complex when the analysis has to be performed on field products that have been used for a certain time under certain conditions. Therefore, a detailed level of information on the product-user interaction is needed. Since reliability means “failure mode avoidance”, the field information should also enable understanding of the failure mechanism.

In order to use the reliability-oriented field information for the purpose of product design improvement, a thorough study of the quality of the information, of the field feedback process and of the processing of the information is first required. Then, the goal is to set the cause and the background of the problem to determine the course of action to be taken in order to reach the optimal solution. It leads to the formulation of the problem and the objective to be tackled in this thesis. The details of the research approach and strategy is explained in the next chapter.
Chapter Four: Research Methodology

The purpose of this section is to define the scope and the content of the research. It discusses the methodological foundation and the research approach used to find an answer to the research questions addressed in this study.

4.1 Research design

A research project needs to incorporate a coherent body of activities, resulting in meaningful and sound insights. The design from this research follows the methodology proposed by [Verschuren & Doorewaard 1999]. According to them, every research design presents a conceptual design aspect and a technical research design aspect (Figure 4.1). The conceptual design is a logical design of the research and the technical research design deals with the realization of the research project. To proceed along this project, a researcher may choose from several research designs and within each design from various data collection and analysis methods.

![Figure 4.1: Research Design (Verschuren & Doorewaard 1999).](image-url)

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4.2 Conceptual design

Research context

In the last few decades, product quality became very important. In high innovative companies, it is difficult to meet the quality and reliability target. The problem arises from the increase in product functionality and complexity, the significant change in business process, the increase in customer requirements, and the strong pressure on time to market. Consequently, the demand for methods to improve quality and reliability management is high.

Therefore, the problem definition for this thesis is:

To operate successfully, companies need to manage product reliability continuously. In an innovative environment, this requires a closed loop control system inside and outside the product development process. In particular, the control system should record the relevant field failures. The former is usually in place and used for design analysis and improvement. However, the field failure data is often used only for the prediction and analysis of spare parts to support supply chain optimization. To be suitable for design improvement, such field feedback process should provide high-quality information at design level. According to the analysis done in the context of this thesis, many design problems are not understood due to inadequate information suggesting that a more efficient method is required.

Research objective

This research focuses on product quality/reliability field information, in particular on its processing and deployment. More and more companies realize that the presently available information is not suitable for product quality improvement [Brombacher2000], and they try to improve the data collection, the metrics used, and the speed of analyzing and using field information. The issue of how to collect field failures and how to process it for improving product design remains a challenge. Therefore, the objective of this research is to analyze the situation in a typical innovative company and to design a solution to improve product quality/reliability by combining field product information and design analysis tools.

The problem definition stated above leads to the following objectives:

The objective of this research is to develop a design method for industries (i.e., industries that design and manufacture “low medium capital industry and consumers” products) that prioritizes design improvement with the help of field information. Then, field information flow (top-down approach) and analysis of individual (potential) failure mechanism (bottom-up approach) are combined to analyze and predict failures. Finally, their occurrence is prevented by implementing design changes that lead to more reliable products by enabling early risk prediction.
Research framework:

The research described in this thesis can be classified as a design practice-oriented research project since the research project aims at designing a solution to improve product reliability performance in a specific company (Figure 4.2).

![Diagram of types of theory-oriented and practice-oriented research project](Verschuren&Doorewaard1999).

In order to carry out successfully this type of research project, the following conditions have to be met: the problem needs to be properly identified and defined, and the problem to be solved must be diagnosed. Next, a method is suggested to reach a solution for the problem. Hence the following research framework is adopted (Figure 4.3):

![Diagram of research framework](Figure 4.3: Research Framework).

Research issues:

This research concentrates on a method to improve product quality/reliability by combining field product information and design analysis methodology. Because most companies make already efforts to gather field information, the next step is to practically use the information for design optimization. A solution is to use the information as input for the design team to reproduce at design level field failures and avoid reoccurrence of them for later generations of products.
Research questions:

In order to reach this research objective, the research study needs to be divided into incremental steps, where successive sub-questions need to be answered.

The first question, which is aiming to identify the problem, is:

- Generic: what are the conditions and constraints from the current product creation process, which lead to a deficiency in reliability prediction in industries that manufacture “low medium capital industry and consumers” products?

The second set of questions, which deal with the diagnosis phase, are:

- Generic: what is adequate reliability-oriented field feedback information? Which criteria should such information fulfill?
- Case study: what is the existing quality of the reliability-oriented field feedback information flow in the company?
- Case study: what is the potential of the field feedback information in terms of design improvement?
- Generic: why is the control loop in its current state insufficient for improving product design?

The third set of questions, which aspire to design a solution, is:

- Generic: what is the best method to improve the analysis of field information?
- Generic: what actions need to be performed to bridge the gap between the available field information and the needed information for design improvement?
- Case study: how do failure modes occur?
- Case study: why do failure modes occur?
- Case study: how to prevent such failure mode?

4.3 Technical research design

Research material

During the research project, the main sources of information are literature and material data provided by the company, where the project takes place.
Research strategy

For the problem finding phase, the literature will provide descriptive knowledge about the general situation for innovative companies and correlate with the problem observed in the industrial partner.

For the diagnosis phase, the intent is to gain a profound insight into a specific process and demonstrate how a situation originates, so that a causal explanation can be given. In this circumstance, the case study is the most appropriate. In addition case studies are preferred when researchers have little control over the event and when the focus is on a contemporary phenomenon in some real life context [Yin1994]. Results form the case study will be compared to the literature available for generalization of the phenomena observed.

In the design phase, due to the specificity of the problem to solve in this research, the analysis is conducted using two different research approaches:

- Field failure analysis (top down)
- Physics of failure [Pecht95] (bottom up).

A field failure approach consists of analyzing the history and current data per product and per failure, combined with feedback from service engineers on customer profiles and the impact they create on product reliability.

The second research line is more theoretical and examines the potential design parameters that play a role in failure mechanism based on physical models. The knowledge reservoir is first consulted to derive hypotheses and prediction.

There is a strong advantage in executing the two lines of research in parallel: most field failure analysis provides data that is not rich enough to fully understand the failure causes; using physics of failure alone will usually lead with problem with a far too high dimensionality to be useful on actual products (too many potential failure mechanisms). Since the two research lines are carried out in parallel it is expected that they will reinforce each other in determining failure causes and underlying design parameters: unlikely failure mechanisms can be rejected because they do not match with field data. Once the correlation with failed products is established, a design solution to avoid the reoccurrence of failures is suggested.
Chapter Five: The use of reliability-oriented field feedback information for product design improvement

As indicated before, product design improvement requires a field feedback process that provides quality information. The reliability-oriented field feedback information should enable a classification of field failures according to the roller coaster model so that the dominant classes of failure are tackled in priority. However, a high level of details allowing root-cause analysis of field failures is not always available. For this purpose, it is suggested to react proactively to the lack of information by combining physics of failure and field information analysis.

5.1 Introduction

Nowadays, companies operating in highly competitive markets will have to be very efficient in developing their products. For this purpose, companies follow a very organized process, in which part of the activities is dedicated to demonstrate technology robustness. According to the maturity of the technology and/or the targeted market of the product, companies choose different product development process strategies. At each stage of the product development process, reliability-related information may be generated, obtained, and updated. Reliability assessments are made periodically as appropriate. However, such strategy requires, especially in the case of innovative products, high quality feedback and control loops in order to achieve efficiency of the total business chain. Total quality and reliability management means continuous improvement. To do so, accurate reliability assessment once the product is in the hands of the customers, should be available and carefully processed. For this purpose, field feedback channels have to be in place. Such aspect is covered in section 5.2.

However, such a field feedback process needs to fulfill certain criteria to provide adequate information. Its content should be clearly defined according to the community, which will use the information. [Evans & Lindsay 1999] emphasizes that people view quality in relation to different criteria based on their individual role in the production-marketing chain. Since this thesis aims at using field information for design improvement, the information content will be defined from the point of view of the design team. Moreover, previous research comes up with recommendations and limitations on the existing systems, which are reviewed in a literature survey. On the basis of the literature survey, a set of criteria is established. All these considerations are detailed in section 5.3.

In section 5.4, a case study is performed within the company. Such case study aims at assessing the quality of the existing field feedback process. In particular, attention is given to the capability and efficiency of the process in terms of product design improvement. However, as it will be shown, the field feedback information is not always
suitable for root-cause analysis so that a method to bridge the gap between the available information and the needed information is suggested in section 5.5. Finally, the complete design of the proposed method is presented in section 5.6.

5.2 Relation between degree of product innovation and product development process

Highly competitive markets will push companies to innovate and develop new products. There are several categories of new products in term of newness to the company and market place [Cooper2001]. For example, [BoozAllenHamilton1982] differentiates six classes of new products: (i) new to the world, (ii) new product lines, (iii) additions to existing product lines, (iv) improvements and revisions to existing products, (v) repositioning, (vi) cost reductions. According to the degree of innovation of a product, companies will adopt a certain type of PDP. Generally, the distinction is made between radical product development process (also known as “new platform”) and derivative products development process (also known as “incremental products”) [Wheelwright & Clark1992], [Veryzer1998]. According to [Ali1994], the three factors that determine what type of new product development is the most appropriate for the company are: the firm or industry characteristics, the market characteristics and the innovation characteristics.

In the context of this thesis, the classification between radical and derivative products is relevant. Since radical products involve higher degree of innovation, it is expected that reliability prediction is more uncertain for radical products than for derivative products. This would imply that reliability management should be conducted differently for radical and derivative products.

5.2.1 Radical products

Radical products involve the development of a new business or new product line, based on new ideas or technologies, or substantial cost reductions. Managers design such products to find specific uses or markets for a promising new technology and expect them to take a relative long time to develop [Ali1994]. Such process is often associated with an uncertain and dynamic environment [Leifer et al 2000].

For example, in the 1990s, the copier/printer industry envisioned a marketplace transformed by computers and networks into a digital document environment. This copier/printer device could copy, print, fax or scan a document to file over communication networks. To realize this vision, the entire office product would be changed from analog copiers to digital copiers through the development of new products platforms. Light lens optical technology would give way to network controller, raster input scanning, and data compression and decompression technology. This change would in turn be accompanied by changes in manufacturing, service and distribution as required by the needs of the new digital market.
5.2.2 Derivative products

In the product development process of derivative products, the emphasis is usually on costs or feature improvement in existing products. They use proven technology to create products based on mature building blocks from existing products. They modify, refine, or improve some product features without affecting the basic product architecture or platform. Such processes usually require substantially fewer resources than processes that develop totally new products. Managers design such products to satisfy a perceived market need and expect these products to take a relative short time to develop [Ali1994].

5.2.3 The need for a field feedback process depending on the type of product

Since radical products entail more uncertainties, companies will optimize their product planning by developing product families based on the same central design [Tatikonda1999]. Such incremental approach (Figure 5.1) reduces the risk involved with radical PDP and has better capability to deal with time to market pressure because it reduces the amount of effort and learning per product type [Minderhoud1999] [Rothwel1994]. Theoretically, such plan of attack allows early market feedback for corrections. However, [Lu2002] observed that quality and reliability problems in time-driven development of derivative products are mainly caused by a bad deployment of the quality-oriented information. [Lu2002], however, focused on information deployment strictly within the product development process between manufacturer-supplier and manufacturer-customer (it being noted that, in [Lu2002] research, the customer is not the end-user). In addition, [Lu2002] did not address field feedback issues.
In this thesis, it is considered that some of the relevant information with regards to product quality and reliability problems is out of the product development process and in the field. In order to reduce risk associated with the second generation of products (derivative products), companies need an accurate assessment of the current product design (radical product) on the market. Predicted and unpredicted reliability problems must be measured and analyzed so that prevention of these problems in the future is ensured (Figure 5.2). Doing so requires the existence of a field feedback process, which brings the necessary reliability-oriented field feedback information to the relevant department.

However, there is still little research which provides examples in which the available field feedback information is actually analyzed and used for product design improvement. Therefore, a definition of reliability-oriented field feedback information needed for design improvement must be established. Such aspect is covered in the next section.

![Figure 5.2: Reliability Field Feedback Process adapted from [Sander&Brombacher2000].](image)
5.3 Design and definition of an analysis system for reliability-oriented field feedback information

The analysis of reliability-oriented field feedback information requires a study of reliability, the field feedback information system/process, and quality of information. For this purpose, the taxonomy of reliability problems is first given. Such taxonomy is used as a baseline to establish the content of the reliability-oriented field feedback information required for design improvement. Then, a review of the research in the domain of field feedback systems is carried out. This review investigates the structure currently used to collect field information, the content of the gathered information, and the problems encountered to generate quality information. On the basis of this literature review, it is shown that other criteria than the content of reliability-oriented field feedback information should be considered.

5.3.1 A taxonomy of reliability problems

Whenever a product is used, there is a probability to activate some failure mechanism, either inherent to the product itself or related to the way the product is used. Therefore, a reliability prediction model will be considered as perfect if it identifies all possible failures and characterizes their behavior (how, when, where). The problem is to come-up with an exhaustive list of all potential failures. Although it is a hard task to forecast all reliability issues and to eliminate all failures [Blischke2000], the design team attempts to predict the product reliability.

Reliability prediction models are often considering failure rate as a function of a “time scale” or “usage factors” that are relevant for the application under study. For example, it might be relevant to study the rate of deterioration of a car engine according to the calendar time, the operation time or the number of starts/stops. The use of different scales might lead to a better appreciation of the problem. It is the designer’s responsibility to study the product reliability using the relevant metrics.

A bathtub curve or failure rate curve is often used to describe the relative failure rate of an entire population of products over a certain “time scale”. Examining the time dependency of the failure rate for a number of components/systems gives insight as to the nature of the failure (infant mortality failures, failures that occur randomly in time, or failure due to ageing) [Lewis1996]. From the engineering point of view, time dependence of failures is also viewed in terms of failure modes, caused either by different mechanisms or by different components of a system.

More recently, it was observed that the failure rate curve was better modeled by a roller coaster shape curve [Wong1988] [Brombacher et al 2005]. Such model distinguishes four classes of failures (Figure 5.3):
Class one: hidden 0 hour failures

Such failures are often attributed to sub-populations of products, which are not meeting customer requirement at time=0. The reasons for failures at t=0 can be that: (i) the product which reaches the customer is outside specification; variability in the manufacturing process is involved for these types of failure, (ii) the product is inside the supplier specification but is unacceptable to the customer either due to an incomplete specification or to a different perception of the product by the customer (misunderstanding in the design process), (iii) the product is deteriorated during transport/handling from manufacturing site to customer site.

For example, in the semi-conductor industry, hidden 0 hour failures may be caused by defects (e.g. crystal defects or dust adhering) occurring during the wafer process which are built in devices. “Burn in” tests are often implemented to weed-out defects and avoid defective products to reach customers.

Class two: early wear-out failures

Such failures are concerned with a sub-population of products operating according to specifications at t=0 but showing, either due to product variability and/or variability in customer use, a deviating performance. This leads to a sub-population of products being reported defective far earlier than the main population of products.

For example, motors which are not refilled with oil when it is required would degrade more rapidly than motors which are carefully maintained.
Class three: random failures

Such failures are induced by random events, either internally in the product or externally, due to customer use or other external influences.

For example, squealing phenomena in brake systems is a random failure. External conditions leading to a change in friction are, among other, a possible cause for squealing. Thus, generally, a more robust design should lower the risks of occurrence of random failures.

Class four: systematic wear-out failures

Such failures are caused by a failure mechanism in products that leads to systematic degradation of the main population as a function of time and / or product use.

For example, the rupture of wind-turbine blade induced by fatigue phenomena corresponds to such class of failure. A preventive maintenance is one of the solutions to prolong operational life of product against such class of failure.

5.3.2 The required reliability-oriented field feedback information content

One task of the product development team is to reduce the risk of failure’s occurrence within product life specification. This implies that companies need to revise their prediction in the light of the field information. Companies seek to get such information to adjust their supply chain, to fit their warranty policy, to prioritize the activities for design improvement, to improve the design of their product, and finally to measure the benefit of such design changes. In order to achieve this objective, companies will therefore collect different types of data from the field.

For reliability analysis, it is suggested that the collected data should allow the classification of the failures according to the roller-coaster model presented above. For this purpose, two approaches can be distinguished:

- The first approach, named statistical failure analysis, deals with failure data (lifetime data). The different classes of failures are determined mathematically using adequate statistical distribution functions. This mathematical approach relies on large samples to increase the confidence of the chosen mathematical model. It requires also an adequate “time scale” and “usage factor” to improve the pertinence of the analysis. Although this approach may allow an accurate prediction of the product reliability, it does not particularly focus on the physical causes of the failures.

- The second approach deals with the analysis of failed product so that the classification is achieved using engineering expertise (i.e. root-cause analysis). It is expected that this approach should bring more insight into the causes of the failures. It implies that the design team should carry out the analysis as it has the best knowledge on the product. The engineering classification is improved when it is combined with the statistical analysis.
For the improvement of the product design, the engineering classification is more adequate. The use of statistical data might however help in the failure classification and in decision-making. Therefore, the information that should be retrieved from the field should permit the following:

- The determination of the absolute number of failed products, modules, components, or better, in proportion to the complete population of product in the field.
- The identification of products that fail more often than other.
- The estimation of product lifetime distribution (using the relevant time scale and usage factors).
- The identification of the different classes of failures (roller-coaster) and failure modes, and the establishment of the lifetime distribution per failure modes.
- The determination of root-causes of failure, in particular the assignment of cause to the manufacturing process, the design itself, the environment, or the user-profile.

The two last items should be interpreted as a combination between the information collected by the field feedback process and the engineering knowledge about the product. [Eppler2003] underlines: “high quality information makes it easier to transform information into knowledge, by helping to interpret and evaluate the information, by assisting the connection to prior knowledge and facilitating the application of the information to new contexts”.

5.3.3 A literature review of commonly used field feedback systems

As a general remark, most of the examples presented in this literature review are illustrations of “best practices” in the electronics industry. The reason is that there are, even nowadays, few academic papers dealing with field feedback process in other industries. Such observation was already made several years ago [Misra1993], but an important deficiency in literature is still noticed. However, the examples mentioned below may help to describe the need to get field feedback information, to gain knowledge on the existing systems, and to analyze the pros and the cons of such systems.

5.3.3.1 The use of field feedback system for reliability prediction

Literature provides examples of different strategies to learn from field failures. [Jones1997] already emphasized the relevance of field data to enable better product reliability prediction. In his work, a database is built-up from field failed electronics components and electronics systems. The database thus enables a prediction of time to failure based on actual operating time for all components, boards or equipments. A comparison of different designs is then possible so that the reuse of the information allows a better identification of potential future reliability problems. However, several
aspects are not very detailed: (i) the time necessary to build such database ("years" is mentioned at the beginning of the article), (ii) the difficulties associated with the build-up of the database, especially how is the data collected. Besides, the root-cause analysis of the failed products is not mentioned.

Later [Blanks1998] also comes to the conclusion that reliability prediction methods for electronics equipment are obsolete. [Blanks1998] suggests that the user of the equipment should participate in the building of a quantitative reliability prediction system by providing feedback on field reliability data to the product manufacturer. Thus the user should (i) establish and maintain an efficient system of failure data collection and analysis, (ii) utilize these data in all aspects of business or organizational activities (iii) participate in the creation and maintenance of an accurate method of reliability prediction. However the author does not explicitly describe the content of the system and neither gives any explanation on how the analysis of the failed product should be performed. [Blanks1998] emphasizes on the need for strong collaboration between supplier-manufacturer and manufacturer end-user to achieve an efficient reliability prediction tool.

[Jackson&Pant2002] present a method to obtain accurate field reliability estimates, which are then used to improve reliability prediction. The system is based on a database containing the following information: (i) manufacturing date, (ii) calendar time as a reference time scale, (iii) product identification so that different designs can be compared, (iv) failure classification according to a predefined failure model. They notice the uncertainty of using calendar time since the time-span between manufactured data and installation date vary considerably from product to product, so that the exact operating time is unknown. However, the model succeeds to highlight deviation between prediction and real product performance. As a conclusion, they suggest several ameliorations to their models, first by increasing the effectiveness of the method in studying environmental factors and second by including deeper root-cause analysis to determine and understand failures especially those arising from a new customer environment.

[Lu1998], [Krivtsov&Case1999], and [Meyer2002] are examples of reliability prediction model from the automotive industry. In such industry, there seems to be difficulties to gather accurate data once the product bypasses its warranty period, so that warranty database is commonly used for such reliability predictive model. The reason behind it is that repairs during warranty period are performed only at authorized dealerships, which probably implies a certain control by manufacturer over the information. Furthermore, the crucial need to gather data using different time scales (e.g. mileage, time in service) is outlined.

As a conclusion, in first attempts to get field feedback information, the focus was to create some "improved" prediction model based on field failed products, so that continuously updated databases could be built-up. Such databases allowed a better estimation of the reliability and product design classification in terms of performance. One can deduce that building-up, and updating on a regular basis, such kind of databases is the minimum required to get an indication on product performance in the field.
However, data processing, as well as the analysis of failed products, was hardly ever addressed.

5.3.3.2 The use of field feedback information for reliability management

The notion of data processing requires that attention must be brought to the difference between data and information. Whereas “data” designates unconnected, quantitative or qualitative items without context; the term “information” relates to answers to questions, statements about situations or facts. In other terms, when a set of data is used to form a coherent statement, the result can be qualified as a piece of information [Eppler2003]. In such context, a change in the terminology is noticeable in the quality and reliability management literature: the term quality/reliability information flow becomes commonly used instead of quality/reliability data.

For reliability analysis purposes, the relevance of gathering data is questionable if it is not associated with an analysis of the conditions in which the failure did occur. Several researches emphasize that field failures are not solely component-related, but result from conditions of use or interactions between modules/parts [Pecht1994], [Brombacher1996].

Therefore, the dilemma for companies is not only to gather single data but also to gather sufficient information to improve root-cause analysis and, at a later stage, for decision-making.

Accordingly, companies need to analyze, predict and improve the reliability of current and future products using reliability oriented information flow. The maturity index on reliability (MIR) model was developed by [Sander&Brombacher2000] to measure the capability of organizations to manage reliability problems. To do so, the MIR focuses on the analysis of reliability oriented information flows. It analyses the response of a business process when a reliability issue occurs and the propagation of the related information through the business process.

The model classifies reliability information flows into five classes (MIR level 0 to 4) as shown in figure 5.4.

MIR level 0: no adequate information available

The manufacturer has no relevant quantitative evidence of the process output (e.g. field behavior) of the products. Consequently, there are no control loops from service back to production and development (e.g. the number of calls of a product is known but not in relation to the age of the products and the number of product sold).

MIR level 1: adequate metrics are in place

The manufacturer has quantitative evidence of the process output in terms of fall-off and field failures and the information is fed-back into the process, but the origin of the problem and/or deviations is unknown.
Figure 5.4: The MIR Model [Sander&Brombacher2000].

**MIR level 2: adequate deployment of information is ensured**

The manufacturer has quantitative evidence of the process output, knows the parties or departments involved (such as marketing, design, production, logistics, etc.), has the corresponding control loop in place and is able to deploy the information to the relevant parties in the product creation process.

**MIR level 3: adequate knowledge on the cause of the failure is available**

The manufacturer has quantitative evidence of the field behavior, is able to deploy the information to the relevant parties in the process and they are able to determine the actual causes to a level where it is possible to resolve the problem.

**MIR level 4: adequate measures are implemented to prevent reoccurrence of similar failures in the future products**

The manufacturer has quantitative evidence of the field behavior, knows the origin of the problems and knows what actually caused them and what to do about it. The level of knowledge is such that the manufacturer not only knows root cause of problems (technical and organizational) but is also able to anticipate and prevent similar problems in the future.

In short, the use of the MIR model for assessing the capability of companies to manage reliability seems an important step in the analysis of field feedback process. The quality of a field feedback process is evaluated at the light of the following elements: the metrics...
used to measure product performance, the deployment of information relating to the reliability problems, the way such problems are analyzed and, finally, the company’s ability to react proactively and modify processes to improve their efficiency. Nevertheless, the MIR model remains general and it can be expected that company’s reactivity might differ according to the type of reliability problems to be solved. In this thesis, the focus is on the use of field feedback system to improve product design, it being noted that the literature only gives few examples of the use on field feedback information for product quality and reliability improvements.

5.3.3.3 The use of field feedback information for product quality and reliability improvements: exploration and limitation

Previous research attempted to cover the use of field feedback information for design improvement and began to study in detail their effectiveness for product quality improvement in a business context.

[Petkova2003] analyzed more in detail the processes used by different manufacturers of consumers electronics to get field feedback. [Petkova2003] divided reliability information flow in two streams, which differ in their purpose: engineering and statistical information. Engineering information is root-cause oriented so that it can potentially be used for product quality improvement. Statistical information gives generally an overall estimation of product quality, but it is mainly used to adjust the supply chain, to fit the warranty reclaim period and to optimize maintenance. The information relevance was judged against two criteria: timeliness and suitability of the information for product quality and reliability improvement. The following conclusions were drawn: the field feedback structure used by the different manufacturers is very similar. Repair center and call center deal directly with customer complaints, before the problem is escalated to the manufacturers.

Such a structure results in important information loss, due to the lack of direct interaction between the product user and the manufacturer so that accurate description (condition of use or environment) is generally lost. Furthermore, the repair center/call center objectives diverge from manufacturer’s ones. The formers need to solve the problem quickly, whereas the latter would like to investigate the root-cause of the failure. Consequently the root-cause analysis is extremely difficult to undertake and leads to failure classification as “not verified”, “fault not found”... With regards to timeliness, the information comes generally too late so that the second or third generation of products is already on the market before the information is available. Consequently, the next generation of product is already on the market, when the first set of information is available to the product development team. The delay is particularly important for statistical information as this requires a larger quantity of failures to be considered as statistically representative.
[Boersma2004] also identifies a large loss of information in the back-end of the development process of companies using service center and/or call center so that root-cause analysis is hardly possible. As a consequence, the information is not suitable for product quality improvement.

Both researches demonstrate that product quality and reliability improvement cannot be achieved because the quality of the field feedback information is poor. The poor quality mainly arises from the existing structure of the field feedback process i.e. the use of repair center and call center to tackle customer complaints.

In the field of information management, several researches stress that data can be relatively easily stored and easily accessible, whereas information should be more carefully handled [Eppler2003]. It is beyond the scope of this thesis to discuss the different frameworks which have been developed in this field of research, but the problems mentioned may likewise be observed when reliability and quality related information flow are studied. For example, in their research on information management [Lesca&Lesca1995] identified eight problems linked to information quality: “(i) limited usefulness of information due to an overload, (ii) ambiguity of the provided information leading to differing or wrong interpretation due to the lacking precision or accuracy, (iii) incompleteness of information that can lead to inadequate decision, (iv) inconsistency of information that leads to confusion, (v) an inadequate presentation format, (vi) information is not reliable or trustworthy, (vii) the information is not accessible, (viii) distortion of the information”.

Accordingly, an inefficient information process might have several consequences: (i) the information cannot be found because it is too dispersed, too vast, incomplete, or inconvenient, (ii) the information cannot be evaluated due to inaccuracy or inconsistency (iii) the information cannot be interpreted due to lack of clarity or incorrectness (iv) information cannot be applied due to a wrong format, a wrong timing, or a wrong application context.

On the basis of these researches, it can be concluded that another criteria should be taken into consideration for field feedback information: the timeliness of the information. In addition, these researches emphasize on the incompleteness of the information for root-cause analysis when customer complaints are tackled in a first instance by repair center or call center. This problem stems from the storage of the field information in field databases. The lack of meaningful information for root-cause analysis using these databases results either from an oversimplification of the customer complaint (use of fault code which is very often a symptom description instead of a cause) or a lack of accuracy (use of free text leading to a difficult appreciation of the information). Therefore, the amount of information is limited when the design team is performing the analysis of the failed product from the field. Moreover, the root-cause analysis is largely compromised due to a lack of contact with the end-user of the product. Therefore, the product design improvement using field feedback information is compromised because of the insufficient quality of the information.
5.3.4 Reliability-oriented field feedback information for design improvement: a set of criteria

On the basis of the literature review and the reliability model adopted for this thesis, it is possible to answer to the first research question:

What is adequate reliability-oriented field feedback information? Which criteria should such information fulfill for product design improvement?

It becomes clear that the quality in reliability-oriented field feedback information relates to certain content, time, deployment and format characteristics, which depend on the specific end-user. It is from the product design improvement prospective that the criteria are hereby specified. In addition, the mentioned criteria should be seen as a whole and not as independent criteria. For example, if the information content is fulfilled, but the time to get the information is far too late, then the interest of having this information is largely compromised.

1. Content

The field databases are usually suitable for collecting information such as the proportion of failed products, the products that fail more often than the other ones, the lifetime distribution of products. For reliability analysis using a statistical approach, the failures registered in the field databases should be stored with the relevant “time scale” or “usage factor”.

Nevertheless, the information content is greatly enhanced once failed products are accessible to the design team. Then the analysis should reach a higher detail level so that the failures should be classified according to the roller-coaster model per product. The classification is based on the engineering knowledge of the design team.

The information should be suitable for root-cause analysis so that failures induced either by the manufacturing process, the design, the environmental conditions or the user-profile should be understood. For this purpose, the process should enable the design team to get, if requested, more information on customer environment or customer profile, so that information can be verified.

The failure classification and the root-cause analysis should be performed on a statically representative amount of products to improve the validity of the analysis.

2. Time

The information related to the reliability of products on the market should be provided as quickly as needed. It should be in line with the time scale of the product development process so that design related problems are understood and, if necessary, design modifications are implemented before the design of the expected next generation of products starts.
3. Deployment

The information should be deployed properly so that the different players in the product development process are aware of the problem, in particular the design team. The loss, the disruption, or the absence of information might prevent an efficient decision-making.

4. Format

The field databases filled by service organization (i.e. call center or service engineer) are usually used to store information on field failed products using pre-defined categories of failures or some free text to describe the failures. However, some of the reliability issues are often unanticipated so that the information required for design improvement cannot always be defined up-front. As a consequence, these field databases are likely to entail several problems with regards to information quality as those mentioned in section 5.3.3.3. Moreover, as the design team merely has access to the databases, but does not create nor feeds them, it can generally not verify the validity and the accuracy of the information included in the databases, which may lead to difficult assessment or interpretation of the information. As a consequence, these field databases should be used as a product performance indicator, but has to be supplemented by other sources of communications.

Other sources of communications should be available to balance the lack of accuracy of these databases, e.g. telecommunications between service engineers (field) and experts of the product (design team) or at best between the customers and the design team. It could enable in certain cases to distinguish failure that occur at single customer and/or single environment.

An important aspect that should be considered when the reliability-oriented-field feedback information is gathered and analyzed is the validity of this information. For this purpose, the mapping of the field feedback process allows establishing the different producers and users of information. Some conflicts of interest between different departments within the organization might lead to the distortion of the field information and should therefore be considered. To counter-measure these effects, the information should be shared and analyzed with people having different skills, experience and different position within the organization (e.g. maintenance, production, engineering and so on) and even with suppliers. The segmentation in business processes tends to create cleavage between teams working on the same project and thus prevents good information and knowledge sharing.

In order to assess the quality of the reliability field feedback information, an analysis should be carried out and should also highlight the main steps of the field feedback process so that the organization of the process is understood. In addition, the information that is generated and processed should be outlined for each step of the process. Such an analysis is performed in the next section in order to answer to the next research question:

*What is the existing quality of the reliability-oriented field feedback information in the company?*
5.4 The evaluation of reliability-oriented field feedback information for design improvement: a case study

In this section, the existing field feedback process is first analyzed. Secondly, the analysis of field failed products at the design level is examined. Thirdly, the potential of the existing reliability field feedback information for product design improvement is assessed. Fourthly, the efficiency of the existing process is benchmarked to other industries.

5.4.1 The analysis of the field feedback process

The first step of the case study consists in the application of the MIR model to the organization. The MIR model aims at classifying the information flows in a company with respect to their ability to measure, to understand and to improve the reliability of a product in the field. A focus is made on the application of the MIR model to the back end of the product development process. The study analyses the successive activities involved in handling product reliability issues when a failure occurs at customer level. The study describes how information relating to the field failure is generated, stored, communicated and more generally, managed. Such information may include the exchange of failed products between the relevant groups, for analysis purposes. The communication between the different groups involved in the process is mapped through interviews.

Besides, the case study will also show if the field feedback information that is generated at each process step fulfills the criteria mentioned in the section 5.3.4.

Two processes, which deal with different products, are presented: product A, aimed at the high volume non-professional market, product B, aimed at the low volume professional market. The results, as presented in figure 5.5 for product A, highlight the reliability information flow in the successive groups: call center, service organization, technical specialist, product engineer manager, and laboratory. In figure 5.6, the results for product B are outlined.

1. Call Center (CC)

The CC is a central phone line that every customer must call when experiencing a problem with a product. All customers are considered equally, as no distinction is made between them. The CC personnel do not know which customer they deal with. They will try as much as possible to solve problems over the phone. The diagnostic of failures through CC has certain limits. First, no link is made between calls from the same customer: the CC has “no memory”. Second, a conflict of interests arises between the CC, whose main interest is to receive a large amount of phone calls, and the manufacturer, who seeks to understand root causes of the problem. Moreover, diagnostic by phone raises issues, since the failure description is mainly dependent on the customer perception and only fault tree charts are used to solve customer issues.
The way problems are solved through the CC depends on the type of failure at stake:

- Failures which are auto-detected by the machine itself and which are identified by a corresponding machine code. Such failures are expected to lead to a correct treatment by CC,
- Failures based on customer description. For such failures, the accuracy of the analysis is more random, which could lead to an excess of replacement,
- Failures which have not been anticipated, and for which the CC has therefore received no instructions regarding its possible treatment. For such failures, the correct advice can therefore not be provided. Until the failure is reproduced in the laboratory and the “Fault Tree Chart” is updated, replacement will be suggested. Therefore much information is lost when such new failures appear.

In conclusion, it can be assumed that the CC will tend to advice replacement of units whenever it is not able to solve the problem. By consequence, a huge loss of information is caused when replacement is advised by the CC, as no information is reported directly to the product development team, whatever the cause for replacement. Product B (i.e. aimed at the professional market) should be less sensitive to this effect, because for such product, the CC stage is bypassed. Nevertheless, the CC generates no information in terms of quality and reliability: consequently its rank is zero in the MIR scale.

Table 5.1: Quality of the information for the call center.

<table>
<thead>
<tr>
<th>Call Center (CC)</th>
<th>The CC provides service and technical support to customer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>The CC decides if the problem requires the visit from the service engineer organization</td>
</tr>
<tr>
<td>MIR level</td>
<td>0 (uncontrolled)</td>
</tr>
<tr>
<td>Information quality criteria</td>
<td>No information is generated for product design improvement</td>
</tr>
</tbody>
</table>

2. Service Organization Engineering Analysis

When an engineering visit is necessary, the information flow is to a certain extent under control. The service engineer has to report his actions after each visit to the customer site. He has to fill in a field database, which consists in indicating: the type of failure (using internal codification) and the part which has been replaced.

Potential mistakes may stem from errors during the reporting in the field database, such as wrong part number/wrong fault code. It is also possible that the service engineer may have made a bad diagnosis and replaced the wrong parts. Nonetheless, changes are traced and statistical data are generated so that the level of information with regards to quality and reliability moves to one using the MIR scale.
Table 5.2: Quality of the information for the service engineering organization

<table>
<thead>
<tr>
<th>Service Engineering Organization (SEO)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
</tr>
<tr>
<td><strong>MIR level</strong></td>
</tr>
</tbody>
</table>
| **Information quality criteria** | **Time:** The information is generated during service engineer visit to customer (service is provided to customer within 48 hours after customer-call for complaint)  
**Deployment:** The information is deployed only if the product engineering manager looks-up the field database or if the service engineer communicates to the technical specialist.  
**Format:** The repair actions are filled in a field database  
**Content:** The information contains statistical information as defined in section 5.3.2 are fulfilled. Different relevant “time scales” are available, and pre-defined failure classifications are used |

3. Technical Specialist

There are technical specialists per country and product. Typically, a technical specialist is able to determine failures that are specific to one customer, to know in which environment each machine works, thanks to the information provided by the service engineers. He has some “memory” and is able to relate one failure with the same kind of failure which may have occurred in the past. The technical specialist receives regular feedback from his service engineers via telecommunications. It is expected that if recurrent failures occur at the same time, service engineer contacts quickly his technical specialist. Furthermore, lists containing all parts replaced by the service engineer are monitored monthly. Thus, an excessive replacement rate is detectable. Regular meetings between technical specialists of each region take place, in which they discuss problems per product, machine and product family, which gives a good comparison between products. It is important to note that, when new products are launched on the market, the link between technical specialist and service engineers is reinforced.
### Table 5.3: Quality of the information for the technical specialist

<table>
<thead>
<tr>
<th>Technical specialist (TS)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>TS manages the teams of service engineers, communicates the field product problems to the product engineer manager (manufacturer)</td>
</tr>
<tr>
<td>MIR level</td>
<td>2-3 (adequate deployment-adequate knowledge on cause)</td>
</tr>
</tbody>
</table>
| Information quality criteria | Time: monthly basis (it can be shortened if necessary)  
  | Deployment: information deployment from the field to product engineering manager  
  | Format: telecommunication, meetings  
  | Content: same information as service engineer plus engineering information so that detail information such as customer-use and conditions of use are potentially available |

4. Product Engineering Manager

One of the roles of the product engineering manager is to survey that the performance of products meets their specified target, and to take some corrective action when products do not reach their expected life. This means that the product engineering manager needs to understand what the defect cause is, and also to disseminate information to the relevant groups: design team, manufacturing, supply chain. He plays a crucial role in the flow of information in terms of reliability and has several tools available to achieve his task.

Information contained in the field database is available, and the product engineering manager uses mainly the following control loops:

- Monthly track of installation and first month performance of new product: such metric covers dead on arrival and early failure.
- Monthly ongoing maintenance rate: such metric is showing whether the design meets its reliability targets.
- Monthly unscheduled maintenance rate: such metric covers unexpected maintenance and it indicates product performance problems. Such metric is a particular early warning signal so that unanticipated reliability issues must be carefully followed-up.

The product engineering manager and the technical specialist communicate on a regular basis so that it is an important complementary flow of information to the field database. In terms of reliability, the interaction between the technical specialist and the product engineering manager is crucial for the understanding of product robustness. Once discussions between the technical specialist and the product engineering manager are established, the information is more detailed and is classified as engineering information. Problems can be monitored in a timely manner and per location. In addition, material flow of failed product/parts can also be requested.
Figure 5.5: MIR analysis product A (high volume, not professional).

Figure 5.6: MIR analysis product B (low volume, professional).
From an engineering point of view, this is a crucial action. The design team can perform detailed analysis on the failed unit. Hence, significant product knowledge is acquired at this level. On such basis, it can be considered that the process is now on the scale between two and three using the MIR scale.

Table 5.4: Quality of the information for the product engineering manager

<table>
<thead>
<tr>
<th>Product engineering manager (PEM)</th>
<th>Function</th>
<th>PEM surveys field product performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIR level</td>
<td>2-3 (adequate deployment-adequate knowledge on cause)</td>
<td></td>
</tr>
<tr>
<td>Information quality criteria</td>
<td>Time: monthly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deployment: communicate field information to the product development team</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Format: field database and telecommunication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Content: same as technical specialist, but he can better related to the product development activities than the technical specialist.</td>
<td></td>
</tr>
</tbody>
</table>

5. Laboratory Failure Analysis

When the failed product reaches the laboratory for failure analysis, the product design team performs two types of analysis.

First, analysis is conducted on products that come back to the laboratory failure analysis for performance problems (warranty reclaim). When the designers investigate the units, several scenarios are likely to occur.

In some cases, the service engineer who sent the unit describes the failure. The design team succeeds to make the same diagnostic, and the root cause is known. Based on statistical analysis, the severity of the failure is estimated and corrective actions are prioritized.

In other cases, the service engineer does not describe the complaint, and the design team is not able to reproduce the failure (i.e. no fault found). The situation then becomes somehow more complex: this inability for the design team to reproduce the failure may be due either to a mistake by service engineer (e.g. engineer has replaced the wrong part), or to a mismatch in the perception of failure between the customer and the design team, or between the service engineer and the design team. The analysis and fault reporting are mainly based on experience from the design team. Each time a failure is diagnosed, a report is brought back to the relevant department (design, manufacturing, service organization …).

Second, analysis is carried out on non-warranty products. Such post-mortem analysis is accomplished on products which may have reached different lives. The analysis aims at having a general assessment of the design robustness. This is important for new products,
especially if an upgraded version of the products is expected using similar technology, as it allows a better understanding of the product design.

In brief, it can therefore be concluded that the MIR level is three-four once the product reaches the laboratory for failure analysis. A complete assessment of the product design is achieved since analysis is carried out on products with different lives. An in depth analysis of the failed product investigation at the design level is presented in section 5.4.2.

<table>
<thead>
<tr>
<th>Laboratory analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
</tr>
<tr>
<td><strong>MIR level</strong></td>
</tr>
</tbody>
</table>
| **Information quality criteria** | **Time:** Warranty-products are analyzed within a month after engineer’s service call  
Non-warranty products are analyzed on a monthly basis  
**Deployment:** communicate the results of the analysis to the concerned department (design, manufacturing, supply chain…)  
**Format:** written report, telecommunication  
**Content:** engineering information such as dominant failures per products and root-cause analysis |

**Conclusion on the field feedback process analysis**

The purpose of the analysis presented above was to assess the response of the existing process when an unexpected event takes place in the field. This analysis demonstrates that there is a product reliability-oriented field feedback. In addition, the process returns statistical and engineering information. The field feedback process in place is able to detect the failure rapidly (1-6 months after market launch) depending on the type of failure, and in any case prior to the start of design of the next product generation.

It is noticed that the field database is used as a product performance indicator, but the quality of the field feedback information is clearly enhanced thanks to communication between the technical specialist (field) and the product engineering manager (product development team). The information deployment relies on these two players.

In addition, the product is surveyed during the totality of its life since an analysis of failed products is carried out on warranty as well as non-warranty products. This enables to perform a complete estimation of the design robustness; it should be anticipated for radical products. After this analysis has been made, the deployment is ensured through communication of the results of the analysis to the involved departments (manufacturing, design, field…).
The time, deployment and format criteria are fulfilled. In the next section, the outcome of the analysis of failed product at the design level is presented.

5.4.2 The analysis of field failed products at the design level

In this section, the analysis emphasizes on the processing of the available information. The limits of the analysis performed by the design team are particularly highlighted.

Once the unit is in the hands of the design team, a specific “time scale” or “usage factor” for that unit is not directly accessible for all products. Whereas such information is available in the field database, it is not necessarily retrieved for all products which are investigated at the design level, as field database searches are time-consuming. Consequently, a pure statistical analysis to estimate the unit life distribution per failure mode is not always possible. The design team identified the absence of relevant “time scale” directly embedded to the product as a crucial lack of information for reliability analysis so that actions have been taken to avoid the same problem/issue for future products.

Second, the conditions in which the product operated is also rarely available. Hence, for some products, insight on failure mode can be obtained only through extra contact with the service engineer. Such approach is achievable for products on the professional market (as the number of such products is rather low and customers are more easily identifiable) but is cumbersome for the high volume market. Accordingly, the root cause analysis of field failures involving possible operational and environmental conditions is extremely difficult when using only field information, due to the large number of factors that might contribute to the failure.

When the design team has access to failed products, it can identify failures per product so that dominant failures are known. However, the content criterion, which consists in establishing a lifetime distribution per failure at design level, is not satisfied for all products. At best, the identification of the different classes of failure is possible for product without relevant time metric. In such case, the classification depends on the engineering knowledge and the interaction with the service engineer. In addition, the information flow analysis shows that further inquiry on customer and environment is potentially available, but will require significant effort.

The foregoing leads to the following observation. Basically, two situations are likely to happen, where either known or unknown failure modes come out from the field. Here, the term “known failure mode” refers to the situation where the same failure has been experienced during the design phase or on a previous product generation. Therefore, the symptoms and the root cause are known. By opposition, “unknown failure mode” is an unanticipated failure mechanism, leaving the design team with a large scope of hypothetical root cause.
5.4.2.1 The analysis of known failure

Known failure modes occur due to different reasons. In this context, the same failure has been experienced at the design phase, but the risk of occurrence has been underestimated, notably because conditions were considered as not sufficiently representative of the complete customer population. In other cases, the reduction in product performance is induced by variability in the manufacturing process. Consequently, the units are out of specification, which means that manufacturing quality process control in place is not capturing unit-to-unit variations. For such types of failure, the current process has the ability to provide rather quick response so that the total number of complaints reduced significantly. In order to improve product robustness, new design implementations are prioritized according to the severity of the problem and the probability of occurrence. It seems obvious that obtaining statistical information is a prerequisite in order to be able to orient decisions for solving the problem.

Therefore, as far as known failure mechanisms are concerned, the poor quality of field feedback information does not necessarily impair their root-cause analysis. The post-mortem analysis is most of the time sufficient to diagnose the failure root-cause even if the analysis is not accompanied with a relevant “time scale” or “usage factor” and precise knowledge on conditions of use. For such types of failure mechanisms, the lack of high quality field feedback information is compensated by the engineering knowledge.

5.4.2.2 The analysis of unknown failure

In case the product failure relates to unknown failure mechanisms seen and reported from the field, the design team cannot provide a straightforward solution. The task imposed on the design team is difficult and time-consuming, notably because the failure is unknown; so that there is no operational definition readily available. One of the consequences will be that different descriptions of the same failure might be given, leading to delay in the information before the correlation is made. For the investigation, material flow from the failed products will help in the identification of the problem. As opposed to known failure modes, accurate field feedback information is absolutely necessary to gain knowledge in the event of unknown failure modes. An accurate description of the conditions in which the failure mode occurred is very useful for understanding the failure mechanism. As already pointed out, the information is not readily available, pro-active actions are required to get more information from the field. If such action is not carried out, the various design modifications might yield poor results.

In such conditions, the root-cause analysis is hampered by the lack of high quality field feedback information. Typically, the lack of “time scale” and/or “usage factor” is considered as a major lack of information. As a conclusion, the quality of the information provided by the current process is not sufficient once the design team faces “unknown failure”.

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Several factors make it difficult to achieve a positive result in such conditions, as:

- there are difficulties in establishing from the beginning the information considered as useful. An inherent consequence will be a delay in the process of gathering information;

- failure data should be collected with time and usage metrics relevant for the product in use. It will allow a better analysis from the field data, and a better classification of the different failure mechanisms. Consequently the design team will be able to measure more efficiently the benefit of the design change implemented;

- a system approach was often neglected. For example, a comparison with other products to reduce the number of potential root causes has not been made. Such approach is useful to rank the contribution of design parameters or the customer profile. Likewise, a lack of cross-functional design teamwork is observed. The segmentation of teams per product is sometimes a barrier for sharing information;

- there is no systematic follow-up and measurement of the benefits expected after a change has been implemented to solve reliability issues, which would be particularly important when the product is designed for the professional market. Indeed, it was found that several customers make themselves changes to the original design if the product does not fulfill their requirement. The biased result is a decrease in the numbers of failure for a specific failure mode, leading the design team to believe that implementing changes was beneficial. Then, the same design will be reused in the next product and the same failure will reoccur.

5.4.3 The potential of the reliability field feedback information: the prioritization of the design problems

In order to use the reliability-oriented field feedback information for the improvement of the product design, a structured approach is required. In particular, the failures that need to be tackled in priority should be identified. For this purpose, a top-down approach divided in three steps is suggested. The method is applied to a radical product presently on the market: product 1. Each product is constituted of several systems and each system is made of several sub-systems.
1. Monitoring product performance

In this step, several indicators are used. These indicators are based on the information contained in the field database. They are showing the product performance and they are already providing useful information. These indicators should be used simultaneously to provide accurate information. The causes for the visits of the service engineers can be retrieved from the field database. It allows the identification of the replaced systems on a monthly basis per product (as shown in figure 5.7). In addition, the causes of the replacement using predefined codifications of the failures can also be identified per system (as shown in figure 5.8). As the replacement might be a scheduled maintenance, attention should be given to avoid misleading conclusions. For this purpose, the average life of the replaced systems of interest should also be retrieved for the considered period of time (as seen in figure 5.9). It can be noticed on the figure 5.9 that the system A has not a stable average life. The design team should therefore understand the causes of these variations.

It can be deduced from this analysis that the product performance monitoring is only providing high-level information. At this time, there is absolutely no evidence of the real causes of the failure from a design point of view. The codifications of the failures, as used in this kind of databases, are only symptom descriptions so that they do not enable the design team to conclude on the robustness or weakness of the design.

2. Failure classification per sub-system at the design level.

As indicated in the analysis of the field feedback process, the design team performs some investigations on the systems that have been replaced by the service engineer. They should enable a more in depth understanding on the causes for the replacement. In particular, some failures might originate from the same sub-system although different engineers might classify the same failure using different codifications of the failures. The design team fills in a technical report that contains, in one column, the complaint described by the service engineer and, in the other column, the root-causes of the failure is given according to the judgment of the design team. An example of a technical report is shown in figure 5.10. On the basis of this technical report, the sub-systems involved in the failure are identified. The results of this analysis are presented in the pie chart of the figure 5.11. This pie chart shows that a large proportion (32%) of the failures originates from the same sub-system (i.e. the cleaningSubsystem) for product 1. The category “other” contains all the other failures because they would have lead to too many categories of insignificant proportion.
Figure 5.7: Proportion of the different systems replaced during the visit of service engineers on a monthly basis for product 1.

Figure 5.8: Classification per failure code for the system A of product 1.

Figure 5.9: Average life of the system A over a certain period of time.
<table>
<thead>
<tr>
<th>Country</th>
<th>Complaint</th>
<th>Root Cause(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>Lines due to blade</td>
<td>PMMA gets loose from blade</td>
</tr>
<tr>
<td>UK</td>
<td>Uneven density</td>
<td>Streaks</td>
</tr>
<tr>
<td>UK</td>
<td>Blade bypass</td>
<td>No problem found after print test</td>
</tr>
<tr>
<td>UK</td>
<td>Cyan bypass inboard side</td>
<td>Used</td>
</tr>
<tr>
<td>Ger</td>
<td>No problem description</td>
<td>PMMA incorrect</td>
</tr>
<tr>
<td>Swe</td>
<td>No problem description</td>
<td>PMMA incorrect</td>
</tr>
<tr>
<td>Ger</td>
<td>No problem description</td>
<td>PMMA incorrect</td>
</tr>
<tr>
<td>Swe</td>
<td>Marks on copy</td>
<td>Drum mech. Damaged</td>
</tr>
<tr>
<td>Ger</td>
<td>No problem description</td>
<td>Used, Screws missing</td>
</tr>
<tr>
<td>Ger</td>
<td>No problem description</td>
<td>Used</td>
</tr>
<tr>
<td>Ger</td>
<td>No problem description</td>
<td>Used</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>No problem description</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>No problem description</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>No problem description</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>No problem description</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>Used</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>Used, Screws missing</td>
</tr>
<tr>
<td>SWE</td>
<td>No problem description</td>
<td>Used</td>
</tr>
<tr>
<td>Swe</td>
<td>No problem description</td>
<td>Drum mech. Damaged</td>
</tr>
<tr>
<td>UK</td>
<td>Cyan bypass from cleaner blade</td>
<td>Torer seal underneath seal, leakage</td>
</tr>
<tr>
<td>UK</td>
<td>Waste auger broken</td>
<td>Screw hole sheath gone, auger broken</td>
</tr>
<tr>
<td>UK</td>
<td>Blade bypass</td>
<td>Torer seal underneath seal, leakage</td>
</tr>
</tbody>
</table>

Figure 5.10: Example of a technical report.

Figure 5.11: Failure classification per sub-system for the system A of product 1.
3. Classification of the failures according to the roller coaster model

In this step, the objective is to sort out the failures according to the roller-coaster model as defined in section 5.3.1. The analysis is carried out at the sub-system level using an engineering approach. In order to improve this analysis, the investigation is enlarged to other products on the market that use the same design of the sub-system. On this basis, the classes of failure that need to be tackled in priority are identified.

The field analysis reveals that product 1 presents a high rate of class one and two failures, to the exclusion of class three and class four failures, attributed to one specific sub-subsystem (i.e. the cleaning-subsystem). It represents 32% of the field failures when they are analyzed by the design team.

In comparison, the same analysis for product 2 leads to a complete different diagnosis. Indeed, the same sub-system using the same design is showing only a small proportion of known, class three, failures. In this case, the same sub-system represents 5% of the field failures analyzed by the design team.

<table>
<thead>
<tr>
<th>Class One</th>
<th>Class Two</th>
<th>Class Three</th>
<th>Class Four</th>
<th>Proportion Failure due to Cleaning Sub-System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning Subsystem (Product 1)</td>
<td>16 %</td>
<td>16 %</td>
<td>Not yet observed</td>
<td>32 %</td>
</tr>
<tr>
<td>Cleaning Subsystem (Product 2)</td>
<td></td>
<td>5%</td>
<td>Not yet observed</td>
<td>5 %</td>
</tr>
</tbody>
</table>

Figure 5.12: Failure classification for the same subsystem on different products.
It is clear that the current process enables detection of predicted and unpredicted failure modes. As far as known failures are concerned, the control loop is functioning well, even if the field feedback information does not fulfill all the criteria previously defined, in particular the lack of information on customer-use or environmental conditions. Nevertheless, for unknown failures, the difficult control/verification of the needed field feedback information and/or the absence of relevant information hamper the root-cause analysis of such failures. Indeed, in such a case, the last content criterion (“analyze the causes of the failure to a level where one can determine whether such failure is induced either by the manufacturing process, the design, the environmental conditions, or the user-profile” set forth in section 5.3.2) is not fulfilled.

Accordingly, the failure classification described in figure 5.12 does help in prioritizing and narrowing down the scope of future actions required for product design improvement. Knowing the classes of failures to be tackled prior to pursuing a root-cause analysis is a significant advantage, as the scope for analysis would otherwise remain too wide. However, the analysis phase for class-two failures should be improved. In order to suggest a suitable method to improve the analysis phase, a review of the current practices in other industries might bring new insights. It is the purpose of the next section.

5.4.4 Why is the field feedback information in its current state insufficient for improving product design?

Brombacher et al. [Brombacher et al. 2005] claim that different business processes require different ways to manage product reliability. Thus, different methods and tools should be available to analyze field failure. Their classification of the different business processes is based on the relation between the economical lifetime of a product and its technical lifetime. The economical lifetime is defined as the average time where it is justified to replace a product for economic reasons, from the manufacturer point of view. If the expected benefits of introducing a new product on the market are higher than the existing performance benefits of a product currently on the market, then a new product may be introduced. The technical lifetime is defined as the average time when a product reaches end-of-life due to technical failures. Three different business processes are distinguished: high-tech, consumer goods, and professional markets (Figure 5.13).

1. High-tech and fast innovation business process

Such process depends on products for which the economical lifetime is much shorter than the technical lifetime. The emphasis is placed on developing products with new features as rapidly as possible to maintain competitive advantage. For example, the introduction of new functionalities, such as integrated camera or MP3 player in mobile phone renders mobile phones with basic functions obsolete.

For such business process, class one and two failures are the most relevant ones. Indeed, for such business process, the product at stake will have been replaced before the class three or class four failures are likely to arise. Nonetheless, the literature review stressed out that, as far as high-tech and fast innovation business processes are concerned, the
field feedback processes existing to date are not able to provide information in-time and the information content is not suitable for product quality and reliability improvement [Petkova2003]. No tools and methods are to date available for design improvement using the field feedback process.

2. Consumer goods business process

Such process involves products where the economical lifetime is comparable to the technical lifetime. Such processes are actually focused on cost, performance and delivery. The type of products studied in this thesis, or products from the car industry, fall in this category. Class one, two and three failures are particularly relevant in the context of such business process.

The case study described in the section 5.4 evidences that, in the context of consumer goods business process, the field feedback information is obtained in-time and suitable for quality and reliability improvement, to the extent that the problem has been experienced during the development-design of the product, i.e. if it is a known failure mechanism. However, field feedback information is not appropriate for unknown failures, in particular class two failures, due to a lack of information with regards to the failure conditions. However, it is noticed that the current process enables design improvement prioritization.

For the car industry, the literature review emphasizes the lack of accurate data once the product bypasses the warranty period: a design assessment founded only on warranty-data does not allow a complete judgment on product performance. No example was found on field feedback data processing for design improvement in such industry. Moreover,
[PateCornell2005] emphasizes: “The National Highway Safety Transportation Administration [DOT-NHTSA2001] is developing a database to deal with an early warning system to prevent accidents due to defective cars, but serious questions have not yet been addressed: what should be collected, how data should be stored, and how the information should be organized and processed”.

As a conclusion, there is no method available in such class of business processes to improve the analysis of failed products from the field.

3. Professional (production) systems business process

Such process involves systems where the economical lifetime is much longer than the technical lifetime. Such systems are characterized by important investments so that they are expected to be used on a long-term basis. Therefore, reliability optimization focuses on system uptime and safety. Aeronautics and nuclear industries belong to such class of businesses.

Class one and two failures are usually avoided through implementation of rigorous quality process controls or in-house testing to guarantee that the failure will not happen during service and endanger system safety. For example, the running-in of mechanical components (e.g. bearings, seals or gears) is conducted by the manufacturer in an optimal manner to ensure system performance. In addition, procedures are normally followed when the system is used, in order to avoid the influence of extreme customer’s behavior/profile. The management of class three and four failures is optimized through the use of safety systems, to reduce and prevent such system to run-out of control, and through adequate maintenance programs.

Nevertheless, the aspect which deserves attention is the efficiency of failure analysis in these industries. A close look at the reasons why such analysis is so efficient might provide insight on the method to choose for root-cause analysis of unknown failure mechanism. In fact, the strength of the analysis resides in a very accurate follow-up of the chains of events which led to the failure. Therefore, reliability improvement in aeronautic and nuclear industries is greatly enhanced by the active field of research in analysis and management of accident precursors [Phimister et al 2005] [Korvers2004]. Precursors are defined as conditions, events and sequences, that precede and lead up to failure or, in the worst case, accident.
For example, the very detailed information regarding the accident conditions, which might be found in an air-crash report [NTSB/ARR-0601] consists in:

- The meteorological conditions when the accident occurred,
- The complete history of the airplane maintenance,
- The complete flight history, including different time scales, such as flight hours, number of take-offs and landings.
- The complete training-history of the pilot,
- The wreckage analysis,
- The cockpit voice recorder,
- The flight data recorder

All human aspects and physical phenomena which could be involved in the accident can be traced back. [Ret2000] stresses that a thorough application of basic failure analysis procedures must be used, but such procedures are often improved by techniques developed to obtain information on events which took place prior to the accident.

In the context of consumer goods business process, such approach remains difficult on account of two factors:

- Customer privacy policy: customer’s behavior cannot be monitored to the same extent, without facing legal issues.
- Business constraints: the implementation of a control device / diagnosis system embedded in products is costly and probably not economically justified in all cases. As a consequence, all product parameters are most of the time not monitored as they are in the aeronautic industry (e.g. flight data recorder) although large developments in signature analysis might be a promising solution for future applications.

Consequently, it is unlikely that the field feedback information alone will provide enough information for design improvement in its current state, and even in a near future, because of the restrictions mentioned above. Therefore, a new method should enable to bridge the gap between the available field feedback information and the information needed for design improvement. For this purpose, the design tools commonly used in the product development phase might improve root-cause analysis.
5.5 Bridging the gap between the available field feedback information and the needed information: the combination of top-down and bottom-up approach

Thanks to the reliability field feedback information, it is possible to prioritize the actions for design improvement. In particular, the dominant class two failures that occur in the field have to be tackled. A system approach (i.e. a comparative study product to product) analysis should be carried out to screen differences in the design, the manufacturing process, and conditions of use so that potential factors involved in the failure mechanism can be deduced. The analysis of failed products (i.e. post-mortem analysis) should also bring insight into the understanding of the failure mechanism. However, as the field feedback information will never be detailed enough, the analysis remains too complex due to the large number of potential factors that might be involved in the failure mechanism. Therefore, complementary information should be used to understand individual failure mechanisms. For this purpose, further actions have to be taken at design/manufacturing level. In the course of the design process, several predictive methods are usually used to anticipate failure modes and find-out the potential root-cause of failure. The combination of the field information (top-down approach) and the design information (bottom-up approach) should be used to derive the most likely failure mechanisms that lead to field failure (Figure 5.14). Afterwards, such predictions are assessed through adequate testing methods. The testing methods should also be considered to explain field failure.

First, the choice of an adequate predictive and testing method are considered and discussed in the following sections.

Figure 5.14: New Method: Combine top-down and bottom-up approach adapted from [Phimister et al 2005].
5.5.1 Reliability predictive methods based on failure mechanism analysis: a review

In a normal design process, once the product specifications have been set, the design team starts anticipating problems that can emerge based on different design concepts. At that time, several technologies might be in the mind of the design team, and predictive tools will help them to select one technology against another one. Several tools are commonly used. They are presented and their applicability in the current context is discussed. Since field feedback information is considered as a top-down approach, other top-down approaches (e.g. Fault Tree Analysis or Reliability Block Diagram) are not reviewed.

In order to strengthen the deductive top-down method, it is strongly advised to focus on a bottom-up approach. For this purpose, literature provides several tools: Failure mode and effect analysis (FMEA) and Physics-of-failure are reviewed. These two methods are retained because there are the only methods that really focus on root-causes analysis.

Predictive method: Failure Mode and Effect Analysis (FMEA)

According to the standard IEEE 352, the objectives of Failure Mode and Effect Analysis (FMEA) are:

- To identify every possible failure mode of a process or product and determine its effect on the required function of the product or process,
- To rank and prioritize the possible causes of failures as well as develop and implement preventive actions, with responsible persons assigned to carry out these actions,
- To develop early criteria for test planning and the design of the test,
- To determine the frequency and impact of the failure,
- To provide input for trade-off studies,
- To provide historical documentation for future reference to help the analysis in the field failures

In general, a multi-disciplinary team performs the FMEA, which is an advantage for complex systems. FMEA is applied in the different phases of the product development process (design, manufacturing) [Stamatis2003].
Table 5.6: Advantages and disadvantages of the FMEA method.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of multi-disciplinary team (information and knowledge sharing)</td>
<td>Difficulties in interpreting interactive phenomena</td>
</tr>
<tr>
<td>Provides a basis for quantitative reliability</td>
<td>Risk arbitrarily estimated</td>
</tr>
<tr>
<td></td>
<td>Does not provide lifetime distribution for a specific failure</td>
</tr>
<tr>
<td></td>
<td>Qualitative method</td>
</tr>
</tbody>
</table>

Predictive method: physics of failure approach

Another approach is the use of predictive methods based on the development of analytical models for the physical-failure of processes or components [Dasgupta&Pecht1991]. For mechanical-electrical components, such model describes the degradation and failure processes arising from different mechanisms. In fact four conceptual models for failure have been set: stress-strength, damage-endurance, challenge-response and tolerance-requirements. The specific failure mechanism depends on material or structural defects, damage induced during manufacture and assembly, and on conditions during storage and field use. Conditions that affect the state of an item are broadly termed stresses (loads), e.g. mechanical stress and strain, temperature, humidity and chemical environment. The difficulty of such model is the customization to fit the application under study.

[Snook et al 2003] underlines the benefit of such a method which consist in modeling failure mechanism, understanding environmental factors and operating loads so that failure within the service life are predicted and eliminated from the design. However, [Hall&Strut2002] stresses the various uncertainties connected to the physics-of-failure method: (i) natural variability in material properties, (ii) effect of variations in manufacturing or assembly process, which may induce further variability into the properties of the components, (iii) uncertainty associated with stochastic fluctuations of operational/environmental influences and stresses, (iv) uncertainty in the formulation of the model to describe the failure process.

[Denson1998] claims that the physics-of-failure has a great advantage since it allows modeling of specific failure mechanism, but claims that it cannot be used to predict field reliability and is not practical to assess an entire system. In the context of this study, these two disadvantages will be examined. The method intends to understand field failure mechanisms so that once the conditions of failures have been determined, early risk predictions are possible. Also such a method can be applied to improve system reliability in the sense that the overall product reliability is enhanced once the individual failure mechanisms are understood.
Table 5.7: Advantages and disadvantages of the physics-of-failure method.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling of a specific failure mode</td>
<td>Not practical for assessing an entire system</td>
</tr>
<tr>
<td>Provide guideline to improve design robustness</td>
<td>Difficult to incorporate different sources of variability</td>
</tr>
<tr>
<td>Provide lifetime distribution for individual failure mechanism</td>
<td></td>
</tr>
<tr>
<td>Can be reused for assessing risk using the same technology</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion:**

In the current context, the physics-of-failure is the best choice for reliability predictions. As the goal is to analyze individual failure mechanisms, the specificity of such method is expected to bring sound insight.

Since the feedback process in the case study provided failed material, the initial step in the analysis is the derivation of hypothetical failure mechanism based on physical evidence. Nevertheless, a missing part is the understanding of the chain of events, which could lead to the failure mechanism. Such gap should be filled through the execution of dedicated test to gain significant knowledge. In addition, the mentioned uncertainties attributed to the physics-of-failure method should be reduced through execution of the tests in controlled conditions and with the help of field feedback information.

5.5.2 Reliability testing methods: a review

In the previous section, the different predictive methods commonly used in the product development process were presented. However, the evaluation of a system-design implies a much broader sequence of activities, which aim to validate the capability of the system to fulfill its intended purpose. To do so the design team should elaborate tests to verify that the product meets its requirements. Much attention must be given to the design of the tests. When not enough attention is given to designing test methods and techniques, the risk of overlooking design flaws is high [Theije1998]. A general approach in the design evaluation is to follow a certain course of action with testing activities. Three types of tests are usually performed: analysis test, verification test and validation test. One should keep in mind that important changes in the design should preferably take place in the early stage of the design process. The reason is that changes are least costly and time consuming when the design concept is less complex and less agreement with third parties have been settled.
5.5.2 Reliability testing method: a review

Analysis test

Analysis tests are normally the first series of tests performed by the design team during the early stage of the detailed design phase. They are usually performed at sub-system level on bench-test with early prototypes to verify certain performance and physical design characteristics. They are also used to explore design weakness so that analysis tests are failure oriented. By doing so, risk assessment of the design is achieved and rapid feedback to the designer is available. Accelerated tests fall in the category of failure oriented tests. Accelerated stress testing is a classical solution for the implementation of tests where product failure needs to be activated faster (and cheaper) in a well controlled environment at the early stage of the product development process. However, a prerequisite for these accelerated tests is a detailed knowledge of the dominant failure mechanism in the product, otherwise irrelevant failure mechanisms might be triggered [Lu2000].

Verification test

Verification tests are carried out after analysis tests and later in the detailed design phase. They are usually conducted with prototypes close to the final product although the design might still be modified. Such tests are success oriented since they aim at showing how good the product is. They check whether failures occur when the product is exposed to stresses up to the design specification stress level of the product. Failures are tracked to define the expected life/performance of the design so that the first estimation of product reliability can be established. However, prototypes produced during the development of a new complex system will usually still contain design and/or engineering deficiencies. Because of these deficiencies the initial reliability of the prototypes may be below the system's reliability goal or requirement. Thus problem areas are identified and appropriate corrective actions (or redesign) are taken. For this purpose, a reliability growth program might be implemented to measure improvement effectiveness. The term growth is used since it is assumed that the reliability of the product will increase over time as design changes and fixes are implemented. However, in practice no growth or negative growth may occur. Reliability growth is due to permanent improvements in the reliability of a product (component, subsystem or system) that result from changes in the product design and/or the manufacturing process.

Validation test

The validation test is the last step in the overall testing phase. The validation is a full integration test. This is the first time that all elements of the system are operated and evaluated on an integrated basis. It is the ultimate test prior to market launch with equipment from the production. Validation tests may include tests at a customer site so that logistics and maintenance support is also validated.
5.5.3 Conclusion

The physics-of-failure is a methodology that enhances reliability by addressing the root-cause mechanism and driving forces responsible for system failures. As a support to the use of physical models, the validation of the hypothetical failure mechanism should be confirmed through dedicated testing. Analysis tests seem the most adequate since they are failure-oriented and suitable to highlight design weaknesses. Therefore, the failure mechanism is reproduced at design level in a laboratory environment: the expected benefit is the controlled conditions in which the experiments are carried out.

5.6 The design of the method to bridge the gap

The suggested method is divided into several steps, and the complete framework is presented in Figure 5.15. The method is designed for the type of products as studied in this thesis: “low medium capital industry and consumer” products. It should be used to tackle class I and II failures.

1. The design improvement prioritization

This step consists in identifying the different classes of failures and failure modes occurring on the products currently on the market (for further details on this step refer to the section 5.4.3). The prioritization is based on the severity of the failures and the relevance of the classes of failures according to the type of business processes. In other terms, failures that are the most costly and that lead to the highest customer dissatisfaction should be treated first.

2. The analysis of individual field failures

Individual field failures have to be understood so that the failure mechanism is identified. If the field feedback information is not detailed enough, the use of design analysis tools such as the physics-of-failure should be used to explain failure mechanism.

The failure analysis is designed to identify: (i) the failure mode (the way the product fails), (ii) the failure location (where in the product the failure occurred), (iii) the physical evidences of the failure, (iv) the time-to-failure, (v) the potential conditions that lead to failure. On the basis of the failure analysis, a first selection of the most likely failure mechanism is achieved. This analysis is also improved with the help of physical models.
Other sources of information that might help in the understanding of the failure mechanisms should also be analyzed. This implies: analysis of the failed products, comparative studies between the failed products and the non-failed products from the same family, and comparative studies between the failed products and the non-failed products from other families. The comparative studies should focus on the potential differences and/or variability in the design, the manufacturing process, and the customer-use.

![Diagram showing the design of the method to improve product design using reliability-oriented field feedback information and physics-of-failure.](image)

Figure 5.15: The design of the method to improve product design using reliability-oriented field feedback information and physics-of-failure

3. The use of guided experiments to reproduce field failures

Before the experimental phase starts two factors should be taken into consideration: time and cost. With respect to cost, the preliminary steps are very important since they should identify the sub-system that fails. It enables to run the experiments on an optimized/minimized experimental set-up (i.e. it avoids running the experiments on complete machine/equipment when the failure is identified on a sub-system). With respect to time, the suggested method focuses on class II failures. These failures show a deviating behavior with regards to reliability so that they occur far earlier than the main population. It is thus expected that the time needed to reproduce the failure is much shorter than the specified operational life of the product.
Failure mechanisms should be reproduced at the design level through experiments. For this purpose, analysis tests seem the most adequate approach since they are failure-oriented and suitable to highlight design weaknesses. The selection of parameters is based on the physics-of-failure analysis and on the above mentioned comparative studies.

4. The root-cause analysis

The experiments are run until the root-cause analysis confirms that the same failure mechanism as seen in the field is reproduced so that it is possible to predict the failure mechanism. During this step, communication with service engineer should be established to validate the findings from the experiments.

5. The product design improvement

The design parameters involved in the failure mechanism are identified. The modification to the design is undertaken in order to prevent the re-occurrence of the failure. The design modifications should be validated by adequate testing.

5.7 Conclusion on the use of reliability-oriented field feedback information for product design improvement

The product development team strives to deliver on the market products which fulfill customers’ expectations and meet reliability targets. To this end, much attention is given to product reliability improvement in the course of the product development process. Different strategies are used to develop a product, according to its degree of innovation. For this purpose, a distinction has been made between radical and derivative product development processes. The former usually entails more uncertainty than the latter, as the use of immature technology (technology newness) and/or unanticipated customer-use (market newness) increase potential reliability problems. Therefore, reliability should be managed differently according to the strategy chosen. In particular, reliability problems encountered with radical products should be carefully analyzed and understood, so that product design improvement can be suggested for derivative products using the same design. Doing so requires a field feedback process which provides sufficient information with regards to field failure.

Therefore, the quality of reliability-oriented field feedback information for product design improvement has been defined according to several criteria. Such criteria have been deduced from previous researches on field feedback systems, reliability problems classification models and quality of information. The following criteria have been chosen: deployment, timeliness, format, and content.

The case study performed within the company reveals that the reliability field feedback information fulfills the criteria: deployment, time, format and content one-two-three. However, the content criterion five (i.e. root-cause analysis) is not always fulfilled. In fact, it is noticed that the analysis of field failed products is successful when the failure has been experienced in the course of the product development process. If the field
failure has not been experienced during the product design phase, the analysis is more complex. In particular, the lack of detailed field information might prevent the success of the investigation.

Although the root-cause analysis in the case study is not always achieved, the existing process enables the design team to distinguish field failures per product, according to the different classes of the roller coaster model. In the prospective of design improvement, such a classification allows a direct comparison of the design performance from product type to product type. Once deviation is noticed for a particular product, prioritization for design improvement can be undertaken. In the presented case study, an important number of class one and class two failures are observed, which therefore had to be tackled in priority.

However, the specificity of class two failures requires the development of a dedicated analysis method. Class two failures are indeed particularly difficult to test because, at product level, products initially perform according to specifications. As many factors might be involved in individual failure mechanism, the lack of information on the events which occurred prior to product failure (notably the conditions of use of the product, and chains of events which led to the failure) hampers the analysis’ efficiency. In particular, the consumer goods industry faces legal and business constraints regarding the information which it may collect on its products. These constraints are less rigid in professional systems, such as aeronautic or nuclear sector, where the existence of strict safety legislation improves the quality of information content.

The method suggested in order to tackle the specificities of class two failures was based on a combination of two existing methods, thus aiming at a better appreciation of the failure mechanism. First, the field feedback information, considered as a top-down approach, consists in analyzing the history and current data per product and per failure, combined with feedback from service engineers on customer profiles and the impact they create on product reliability. Second, a bottom-up approach could bring complementary information. The physics of failure was chosen as the most appropriate bottom-up approach, since it focuses on the understanding of individual failure mechanisms. Such an approach is more theoretical and examines the potential design parameters that play a role in failure mechanisms, based on physical model. Both methods, taken separately, entail a large uncertainty, but may reinforce each other in determining failure causes and underlying design parameters, if carried out in parallel: unlikely failure mechanisms will be rejected because they do not match with field data.

Related to the case study, this chapter highlighted the classes of failures which need to be tackled in priority, and pinpointed the sub-system responsible for such failures. In the next chapter, an in-depth analysis of the field information and the application of the physics-of-failure are carried out to understand individual field failure.
Chapter Six: The analysis of individual field failures

In the previous chapter, it was shown that due to the lack of detailed information from the field, a deep understanding on the field failures is hardly possible. Therefore, a further step in the analysis is required. Individual failure mechanisms should be understood by combining field feedback information and physics-of-failure analysis. The analysis is carried out and shows that the selection of the most likely failure mechanism is possible.

6.1 Introduction

In the previous chapter, a method has been proposed to tackle field failures using reliability field feedback information and physics-of-failure approaches. As the study is made with an industrial partner specialized in the copier-printer industry, the method is applied to their products currently on the market. The prioritization for design improvement carried out in the previous chapter highlights some dominant failures of class one and two. The field feedback information enables to pin-point the sub-system where these failures occur.

In this chapter, the step that consists in analyzing individual failure mechanisms is undertaken. For this purpose, a more detailed description of the studied sub-system is required. Therefore, a short description of the xerographic process is given in section 6.2 in order to introduce the cleaning process, its functionality and its design. In section 6.3, this cleaning sub-system is characterized using a physical model (i.e. a tribological description). In section 6.4, a model using the finite element method that enables a better description of the cleaning-subsystem is presented. Then, an analysis of failed products from the field is carried out in section 6.5. Finally, the analysis of failed products with the help of physical models leads to the selection of the most likely failure mechanisms derived from the physics-of-failure. This selection is argued in section 6.6.

6.2 Functionality and design of the relevant sub-system

The purpose of this section is to describe the functionality and the design of the sub-system under study. However, it is advised to use a system approach description so that the role of the sub-system in its complete environment is given. It might help in the understanding of the failure mechanisms (i.e. potential interaction phenomena) and it might also give insight into the constraints of the design. An in-depth analysis of the knowledge gained during the development of the design is also carried out. In the later phase, such as the optimization phase, the suggested design modifications should also be taken in consideration of the other sub-systems.
6.2.1 The xerographic process

The function of the xerographic process is to produce a quality permanent image on plain paper.

The basic steps and elements of the xerographical process are described. The photoreceptor drum is an essential part of the process. This is an aluminum drum with a photoconductive coating. The drum rotates with a given process speed and moves along the following steps (Figure 6.1):

1. Charging

On the drum surface, an electrostatic charge is applied up to a constant electrostatic voltage. In the example that is shown here, the component that charges the drum is a corotron. This consists of a tungsten wire (corotron wire), partly surrounded by a metal shield. Between the wire and the shield, a voltage difference is applied, high enough to cause gas discharge. The charged particles from this discharge (or: corona) electrostatically charge the drum.

2. Exposure

In this step, the image to be printed is “written” on the drum surface. On the spots that correspond to “black” on the image to be printed, the laser illuminates the drum surface. Since the drum coating is photoconductive, the electrostatic charge leaks away on that spot. At the end, the image is on the drum as an electrostatic charge pattern, also called latent image. Black (image) corresponds with a low charge density or a low electrostatic voltage (Vlow), white (background) corresponds to a high density or high electrostatic voltage (Vhigh).

![Figure 6.1: The xerographic process (for explanation see text).]
3. Development

In this step, the latent electrostatic image is converted into a “real” toner image. Toner or components within toner are magnetic and are attached to a magnetic roll to form a toner brush. The toner particles are tribo-charged to a certain level. The magnetic roll is biased to a voltage that is in between Vhigh and Vlow. For the black areas, the electrostatic voltage on the drum is lower than the magnetic roll voltage and the charged toner particles are attracted to the drum by the electric field (also called: developer field). For the white background areas, the electrostatic drum voltage is higher than the magnetic roll voltage and the resulting electric field (called: cleaning field) repels the toner particles from the drum. The result is a developed toner image on the drum.

4. Transfer

Now the toner is transferred from the drum onto the substrate (i.e. paper sheet or transparency). The concept is that the paper is brought against the drum and that the back of the paper is electrostatically charged. This electrostatic transfer charge attracts the toner particles from the drum surface to the substrate. There are few techniques to apply this transfer charge, but in the example above this is done by a corotron.

5. Detack

Due to the electrostatic forces caused by the transfer charge on the back of the substrate, the substrate is tacked to the drum. In order to strip the substrate from the drum, the transfer charge on the back of the substrate is partly neutralized. This is achieved by another corotron, the detack corotron. In this example, the detack corotron contains two corotron wires.

6. Erase

After the process described above, the drum still contains electrostatic charge and residual toner. This electrostatic charge is removed by illuminating the photoreceptor with a LED array so that all the remaining charge leaks away.

7. Cleaning

In this step, all residual toner is removed from the drum surface. Again, a number of different techniques can be applied, but in this case cleaning is achieved by setting a polyurethane cleaner blade against the drum, which scrapes the toner from the drum.
High-speed xerographic printing, copying and duplicating involve cyclic repetition of the steps as described above. Residual toner must be removed from the photoreceptor before any process cycle is started. Otherwise, residual toner can become permanently attached to the photoreceptor surface, thereby altering its electrical nature and finally resulting in copy quality defect. Cleaning failures occur in several ways, and they are the results of different failure mechanisms. This thesis focuses on the cleaning process since an important number of failures involving the cleaning-subsystem are reported from the field.

6.2.2 The cleaning system design

When toner particles are transferred to the paper, some particles are left behind on the photoreceptor surface. As the studies of [Mastrangelo1982], [Hays1988] and [Meyer2000] show, electrostatic (Coulomb) and dispersion (Van der Waals) forces are responsible for toner-photoreceptor adhesion. It is during the product design phase that the toner and photoreceptor properties, as well as the blade design parameters, are adjusted to meet the required cleaning efficiency and reliability goal. However, the cleaning sub-system must be able to clean the surface independently of the operational conditions, and of the consequences they can have on the adhesion between toner and photoreceptor.

As a design tool for a direct determination of the sub-system critical specifications is missing, these specifications (Figure 6.2) are selected after a series of tests (analysis-verification-validation) that determine the boundaries in which the cleaning sub-system is able to clean efficiently and to meet the reliability goals. It leads to the so-called operational window (latitude window) for a cleaning subsystem. A generic example of such an operational window is given (Figure 6.3). It is defined according to two critical parameters: the blade load and the working angle.
Design critical specifications:
- $L$: free length (FL)
- $\theta$: blade setting angle (BSA)
- $D$: blade interference (BI)
- $T$: blade thickness (BT)

Critical parameters:
- $\alpha$: working angle (WA)
- $N$: normal force (NF)

Figure 6.2: Cleaning subsystem design parameters.

The four distinctive zones, which delimit the cleaning latitude window, are (Figure 6.3):

- “Excessive wear”: this zone concerns either the blade or the drum coating wear. It might lead to an accelerated wear-out phenomenon and result in a shorter life of the system with respect to the reliability goals. Such boundary requires testing until the expected end of life of the product. An alternative method to testing could be to calculate the wear rate coefficient and to extrapolate until the expected end of life, based on data stemming from previous products.

- “Planing”: this zone results in a poor cleaning efficiency. Such a failure is quasi-instantaneous and is characterized by some band of toner bypassing the blade all along its length. The “planing” condition is characterized by working angle being so low that failures occur even at blade loads where cleaning would be fine with higher angle.

- “Pressure too low”: this zone results also in poor cleaning efficiency. Such a failure is quasi instantaneous. As opposed to “planing”, such a failure is characterized by load being so low that failure occurs even at working angle where cleaning would be fine with higher load.

- “Chattering”: this zone results in intermittent poor cleaning efficiency. The root-cause is not clearly defined even if chattering is often a self excited vibration based on the stick-slip phenomenon. It is very dependent on system stiffness,
speed and relation between static and kinetic coefficient of friction [Gao1994]. Consequently, the failure mode is also very dependent of the operational conditions.

6.3 The physical description and the potential failure mechanisms of the sub-system under study

In this section, the study emphasizes on the different physical phenomena that describe the sub-system. For this purpose, the literature and historical design information are reviewed. On this basis, the potential failure mechanisms that might occur on the sub-system are identified. It is a relative broad study where all possible options are considered. The selection of most likely failure mechanisms are done in a later stage when the failed products are analyzed.

In the context of the study, the domain of knowledge that governs the cleaning system is called tribology. Tribology is defined as: the study that deals with the design, friction, wear and lubrication of interacting surfaces. The design was presented in the previous section. This section will provide insight on friction, wear and lubrication in the xerographic context.

6.3.1 Friction

Friction is the resistance to motion, which is experienced when one solid body moves tangentially over another with which it is in contact. The resistive tangential force, which acts in a direction directly opposite to the direction of motion, is called the friction force [Hutchings1992].
There are two basic empirical laws of friction for dry conditions, based on empirical observations and relatively accepted for centuries since the work of Leonardo Da Vinci [Amonton1669]:

- The tangential friction force is proportional to the normal force in sliding;
- Friction force is independent of the apparent contact area;

Further work [Bowden&Tabor1964] leads to the identification of two components in friction phenomena. One component is induced by interfacial adhesion between contact bodies. In addition to the frictional energy to overcome adhesion developed in the real areas of contact between the surfaces (asperity contacts), the second energy component arises from micro-scale deformation of contacting surface during sliding.

The adhesion strength at the interface depends upon the mechanical properties and the physical and chemical interactions at the interface. The junctions sheared under the applied tangential force results in the frictional force. There are several ways to reduce the adhesion component of friction. Firstly, the presence of film lubricant with low shear strength characteristics between the two contacting bodies can be used to reduce adhesion strength. Sometimes the presence of contaminants from the environment or wear debris resulting from the contact will also result in lower adhesion.

Secondly, the reduction in the real contact area is also a way to minimize the friction induced by adhesion, which could be achieved either by reducing the pressure or increasing the hardness (Figure 6.4). The adhesion part of friction for rubber material also involved a complex adhesion and re-adhesion process. Frictional work is associated with the energy lost during the continuous de-adhesion and re-adhesion process [Burgin1962], [Schallamach1971]. Thus the damping properties of the rubber material are influencing the adhesion friction.

Figure 6.4: Contact situation between two surfaces. Only small parts of the surface are in real contact with each other. The area of real contact increases with increased pressure and lower hardness.
A deformation component of friction occurs in visco-elastic material in the so-called elastic limit, because of elastic hysteresis losses [Bushan1999]. When an element of volume is stressed, elastic energy is taken up by it. When the stress is removed from the element, most of the energy is later released. A small part is lost (in the form of heat) as a result of hysteresis losses. Such dissipation of energy results from the non-ideal elastic behavior of rubber material (Figure 6.5). The net loss of energy is related to the input energy and the properties of the rubber at the particular temperature, pressure and rate of deformation of the process [Moore1972] [Ludema&tabor1966].

![Figure 6.5: Fluctuating stress induced by asperities gives rise to energy dissipation via internal friction of the rubber.](image)

The coefficient of friction is not an inherent material property; it depends very much on the two materials in contact, the operating conditions and surface conditions. During sliding, changes in the conditions of mating surfaces occur, which affect friction and wear properties.

### 6.3.2 Wear mechanisms and their consequences on the cleaning system

In this section, the discussion is focusing on the wear mechanism classification reviewed from the literature.

Wear is the surface damage or removal of material from one or both of the two solid surfaces in a sliding motion relative to one another. Wear, as friction, is not a material property, it is a system response. Operating conditions affect interface wear. Erroneously, it is sometimes assumed that high-friction interfaces exhibit high wear rates; this is not necessarily true [Persson2000].

The literature provides six principal and distinct wear phenomena: (i) adhesive, (ii) abrasive, (iii) fatigue, (iv) impact by erosion, (v) chemical, (vi) electrical-arc-induced [Hutchings1992], [Bayer1994]. During operations, several wear mechanisms can occur at the same time or alternatively. Failed components are generally examined to determine the type of wear mechanism responsible for the failure. In the present system, the adhesive, fatigue and abrasive wear mechanism are likely to occur.
Adhesive wear

This wear mechanism results from the shear of the friction junction. Such wear mechanism remains directly related to the adhesive component of friction. Adhesive wear occur mainly when the counterface is smooth and involves the transfer of polymer to the harder counterface and its subsequent removal wear debris [Hutchings1992], [Bely1982]. Such mechanism can result in a very high wear rate and large unstable friction coefficient [Stachowiak2005]. The surface properties of the two contacting bodies play a primary role resulting in a certain coefficient of friction. If the wear needs to be minimized then the adhesion between the contacting bodies should be low.

Abrasive wear

Abrasive wear occurs when asperities of a rough, hard surface or hard particles slide on a softer surface and damage the interface by deformation or fracture [Myshkin2005]. When the damage results from the asperities of the harder surface, it is a two-body abrasion mechanism. When the damage results from an external body, generally a small particle of abrasive that gets trapped at the interface, then it is a three-body abrasion. In this context, hard particles mean that they are in the same order or harder than the surface they are loaded against. In most abrasives wear situations, scratching is observed as a series of grooves parallel to the direction of sliding.

Fatigue wear

Fatigue is known to be a change in the material state due to repeated (cyclic) stressing results in progressive fracture. A friction contact undergoes cyclic stressing during sliding. Its characteristic feature is the accumulation of irreversible changes, which gives rise to generation, and development of cracks. Thus wear under these conditions is determined by the mechanism of crack initiation, crack growth and fracture. Generally, it is observed that the cracks are initiated at the points where the maximum tangential stress or the tensile strain takes place [Myshkin2005]. They are located either on the surface or in the sub-surface depending on the friction coefficient. However other factors influence fatigue life of rubber: the mechanical loading history (static loaded period, load sequence, minimum and maximum strain-stress oscillation, frequency), the environmental conditions (temperature, oxygen, and ozone) and the formulation of the rubber compound (elastomer type, filler type, curatives) [Mars2004].

6.3.3 The modes of lubrication in the cleaning sub-system

For the cleaning process, it is obvious that the interactions between the main components: drum, toner and the blade play a central role within the performance of the cleaning system. The objective of the application is to provide good cleaning efficiency and to minimize the two main disadvantages of solid contact: friction and wear. In order to minimize friction and wear, sufficient lubrication should be available at the blade edge.

For lubrication purpose, two different lubricants are presently in use. A Poly Methyl Meth Acrylat (PMMA) powder is applied directly to the blade edge during the cartridge assembly process. The PMMA provides lubrication to the cleaning system for the first
cycle-in of the machine. In such a case, the PMMA is used to prevent the adhesion component of the friction coefficient. When the blade and the drum are in contact for the first time, their surfaces are extremely smooth and clean. Thus there is a need to prevent direct contact between these two surfaces to lower the adhesion strength. In fact, the PMMA layer plays a more complex role in the lubrication process, as it will be explained later in this thesis. During the operational running conditions, the toner and its additives provide the second source of lubrication.

The toner falls in the category of solid lubricant. Solid lubricant is any material that is used as a powder or a thin, solid film on a surface to provide protection from damage during a relative movement by reducing wear and friction [Bushan1999]. Toner is defined as polymeric spherical particles with a particle size varying from five till ten micrometers on average. The toner is blended with additives, which have different functionalities due to toner’s implication in nearly all steps of the xerographic process.

The additives used are to:

- Control toner charge and toner flow (development),
- Reduce the toner adhesion to the photoreceptor surface (transfer),
- Optimize transfer efficiency (transfer),
- Furnish lubricant properties (cleaning system).

Two classes of additives are commonly used: filming lubricant and spacers. These additives are not exclusively used to lubricate the cleaning subsystem but they can be helpful to optimize the cleaning effectiveness (increase cleaning latitude). As an example, the cleaning operability could be improved if the filming lubricant has the following properties: (i) adhere strongly to the photoreceptor, (ii) adhere weakly to the cleaner blade, (iii) have a large lubricant monolayer thickness on the photoreceptor and a low monolayer thickness on the blade [Meyer2000]. Spacers are also used to reduce toner adhesion to the photoreceptor and toner cohesion, which enable also an increase in cleaning latitude. However, experiences on some of the products prove that the toner and additives have in certain conditions undesirable effects such as abrasive behavior. It could results in excessive damage on the cleaner blade or damage on the photoreceptor surface and jeopardizes the life of the system [Hirsch2001].

Extensive research is still underway to optimize the toner constitution and its interaction with the cleaning blade. For this purpose, several aspects should be covered. First the exact particle detachment process of the toner at the blade tip should be identified. Several mechanisms are likely to occur: rolling, sliding and lifting detachment process. For each of these processes, lubricant properties could be optimized to increase the cleaning latitude.

Second a perfect understanding on the lubrication regime at the interface blade-photoreceptor is required. For this purpose, the development of the “quasi hydrodynamic
lubrication” theory is promising. [Hesmat1992] demonstrated that a number of basic features of powder flow in narrow interfaces exhibit the characteristic behavior of fluid film lubrication. Thus powder with very small particles size (1-10 µm) functions like a continuum with velocity and shear characteristic of hydrodynamic fluid film. Consequently, it is expected to have different operating regimes of lubrication: dry friction, boundary, mixed, hydrodynamic and limiting shear stress.

From the theoretical point of view, there are still difficulties to characterize the rheological behavior of powder. The calculation requires one important input: the powder viscosity. Currently, such measurement has not yet been successfully addressed at the temperature of interest, when the toner is in its powder state below its melting-temperature. Moreover, during the aging process, the different contaminants made of debris from the photoreceptor top layer, paper debris and dusts lead to a very inhomogeneous powder constitution. Thus the rheological characteristics normally required for the film thickness calculation are very difficult to extrapolate.

From the experimental point of view, there are no successful measurements of the lubrication regime during a run. Such measurements could provide deep insight on the exact lubrication regime seen by the system at different stages of its life.

All the phenomena described in this section are likely to occur in the contact between the blade and the photoreceptor. In order to have a better understanding on the contact, the next section will present the simulation work made to describe accurately the contact.

6.4 Physics of failure using computational model

In this section, some simulation tools are used to gain better insight into the dominant mechanisms that influence the sub-system. It allows studying the influence of the design parameters in relation to the physical models that have been identified. For this purpose, some analyses, using the finite element method, are performed. The operational conditions and the design of the sub-system are used as inputs of the simulation.

For a specific drum-blade combination and its prescribed design and material critical specifications, the cleaning blade operational window is characterized by two critical parameters that can be adjusted: the blade load and the blade working angle. The influence of those two critical parameters on the cleaning system behavior (cleaning efficiency and system reliability) is generally studied during the design phase. However, such parameters do not enable an accurate description of the blade-drum contact. Nowadays, tools like the finite element method (FEM) offer the possibility to do such calculations. Accordingly, a model is developed to gain insight on the contact blade-photoreceptor.
Several aspects like the non-linearity of the configuration under study are taken into account:

- The hyper-elastic and visco-elastic behavior of the rubber material
- The contact phenomena involved (non linear boundary conditions)
- The coefficient of friction (non-linear boundary conditions)

This section aims at providing new insights on the previously described cleaning subsystem operational window by studying particularly the contact pressure distribution. The characteristics of the contact pressure distribution are: the contact width, the maximum pressure in the contact, the contact-pressure gradient, and the stress distribution in the blade nip. The following critical specifications are inputs for the simulation: blade interference, blade setting angle (BSA), blade thickness, blade free length, and blade material properties. However, the blade setting angle and blade interference allow an exploration of the complete latitude window. Therefore the presented results show the major effect of these two design specifications on the contact pressure distribution. Later, the effect of friction on such contact pressure distribution is also introduced. It is expected that the optimization of the cleaning system is the balance between a sufficient contact pressure to maintain a good cleaning efficiency and a convenient stress distribution to avoid a rapid deterioration of the cleaner blade and/or the drum surface.

6.4.1. The contact pressure distribution

The results are displayed (Figures 6.6-6.11) for different blade interferences (0.8 mm, 1.4 mm and 2.0 mm) and different blade setting angles (20 degree, 25 degree and 30 degree). The table 6.1 summarizes the numerical results obtained for the different simulations, and focuses on three outputs: contact width, maximum peak pressure within the contact, and pressure gradient. On purpose, these values (i.e. interference and blade setting angle) are taken in a range slightly larger than the normal product specification. It is an exploratory phase rather than an optimization phase. Later in the design phase, the use of robust design methods should be considered to evaluate the weight of each design parameters on the pressure distribution characteristics. This aspect is not covered in this thesis.

For discussion hereby, the case of blade setting angle equals to twenty-five degrees at different blade interferences is chosen (Figures 6.8 and 6.9). Such an example is relevant since it covers three of the distinctive zones of the generic operational window of the cleaning sub-system. All simulations are run in frictionless static mode.

The following important remarks can be drawn:

- Case blade interference equals to 2 mm: the system is said to be in the “planing” condition, which results in poor cleaning performance. In this configuration, a relative low peak pressure compared to the other configurations characterizes the contact pressure distribution. Besides, the pressure is distributed over a large
contact width. Such a pressure distribution is insufficient to guarantee good cleaning efficiency. Thus, an increase alone in the blade interference will contribute to a higher blade load, associated with an increase in the contact width and a decrease in the peak pressure.

- Case blade interference equals to 0.8 mm: the system is susceptible to chattering phenomena, which can also lead to squealing phenomena or intermittent cleaning failure. In comparison to the “planing case”, important variations in the pressure distribution characteristics can be noticed. Effectively, the contact width is largely reduced. However, the peak pressure is increased. Thus, a decrease alone in the blade interference will contribute to a lower blade load associated with a decrease in the contact width and an increase in the peak pressure.

- Case blade interference equals to 1.4 mm: the system is performing well in terms of cleaning efficiency and reliability. As expected, the contact area and the peak pressure fall in between the values from the two extreme cases mentioned above.

In order to use the finite element model as a proper design tool, it seems pertinent to determine the optimal combination of the contact width, the maximum peak pressure and the pressure gradient required to obtain good cleaning and reliability. Then, the design parameters specifications should be chosen to obtain this optimal combination. As an example, the variability of these three characteristics according to the blade interference and blade setting angle is presented in frictionless and in friction state (coefficient friction equals to 0.5) for a given configuration (young modulus, free length, and blade thickness considered as constant) in figures 6.12-6.17:

- Contact width in function of interference and blade setting angle:
  \[ W = f(d, BSA) \]

- Maximum peak pressure in function of interference and blade setting angle:
  \[ P_{\text{max}} = f(d, BSA) \]

- Maximum pressure gradient in function of interference and blade setting angle:
  \[ (dP/dx)_{\text{max}} = f(d, BSA) \]

6.4.2 The effect of friction on the contact pressure distribution

Under operational conditions, it is very likely to see variations in the coefficient of friction since the lubrication level is not necessarily constant over time. Consequently, it is interesting to analyze the friction effect on the contact pressure distribution. For this purpose, several simulations are run in static mode with the introduction of a coefficient of friction. The coefficient of friction is ramped-up from zero to a value of 0.5. The resulting contact pressure distribution corresponds to the stabilized-equilibrium state of the system for the given friction coefficient.
The simulation shows a strong effect of friction upon the pressure distribution. The two main effects for a given configuration are the following ones: a reduction of the contact width and an increase in the peak pressure. The results from different configurations are summarized in the Table 6.2. During all these simulations, the coefficient of friction is ramped from zero to 0.5.

The table should be read as follows. The column “contact width reduction factor” represents the reduction factor in the contact width between the frictionless and the friction configuration. The column “peak pressure” represents the multiplication factor in the maximum peak pressure between the frictionless and the friction configuration.
Table 6.1: Numerical results in frictionless conditions for contact width (W), maximum peak pressure (Pmax), and pressure gradient (P gradient) for different blade setting angles (BSA) and blade interferences.

<table>
<thead>
<tr>
<th>Interference</th>
<th>BSA=20º</th>
<th></th>
<th>BSA=25º</th>
<th></th>
<th>BSA=30º</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W (mm)</td>
<td>P Max (MPa)</td>
<td>P grad (MPa/mm)</td>
<td>W (mm)</td>
<td>P Max (MPa)</td>
<td>P grad (MPa/mm)</td>
</tr>
<tr>
<td>Interference=0.8mm</td>
<td>0.021</td>
<td>2.00</td>
<td>1336</td>
<td>0.016</td>
<td>2.57</td>
<td>1748</td>
</tr>
<tr>
<td>Interference=1.4mm</td>
<td>0.064</td>
<td>1.40</td>
<td>1205</td>
<td>0.042</td>
<td>1.99</td>
<td>1327</td>
</tr>
<tr>
<td>Interference=2.0mm</td>
<td>0.226</td>
<td>0.585</td>
<td>758</td>
<td>0.102</td>
<td>1.29</td>
<td>1122</td>
</tr>
</tbody>
</table>
Figure 6.6: Frictionless static contact pressure at constant BSA=20°.

Figure 6.7: Zoom on peak pressure.

Figure 6.8: Frictionless static contact pressure at constant BSA=25°.

Figure 6.9: Zoom on peak pressure.

Figure 6.10: Frictionless static pressure at constant BSA=30°.

Figure 6.11: Zoom on peak pressure.
Figure 6.12: Contact width in function of BSA and interference.

Figure 6.13: Contact width in function of BSA and interference (coefficient friction=0.5).

Figure 6.14: Maximum peak pressure in function of BSA and interference.

Figure 6.15: Maximum peak pressure in function of BSA and interference (coefficient friction=0.5).

Figure 6.16: Pressure gradient in function of BSA and interference.

Figure 6.17: Pressure gradient in function of BSA and interference (coefficient friction=0.5)
Table 6.2: Effect of friction (f=0.5) on output width (W), maximum peak pressure (Pmax) and peak pressure gradient (P gradient) for different blade setting angles (BSA) and blade interferences.

<table>
<thead>
<tr>
<th>Friction</th>
<th>BSA=20°</th>
<th>BSA=25°</th>
<th>BSA=30°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W</td>
<td>P Max</td>
<td>P gradient</td>
</tr>
<tr>
<td>Interference=0.8mm</td>
<td>x 0.62</td>
<td>x 2.4</td>
<td>x 1.56</td>
</tr>
<tr>
<td>Interference=1.4mm</td>
<td>x 0.66</td>
<td>x 3.4</td>
<td>x 1.64</td>
</tr>
<tr>
<td>Interference=2.0mm</td>
<td>x 0.75</td>
<td>x 5.0</td>
<td>x 2.36</td>
</tr>
</tbody>
</table>

Interference: 0.8mm, 1.4mm, 2.0mm
In addition to the above-mentioned effects, another underlying effect of the friction coefficient is the displacement of the maximum peak pressure within the contact. Such an effect is noticeable for all configurations but is stronger at low interference and high blade setting angle. For illustration, an example is given. It corresponds to the configuration (BSA=30° and Interference= 0.8 mm). First the pressure distribution in its frictionless state (Figure 6.18) is portrayed as well as the resulting pressure distribution with friction (Figure 6.19). In order to emphasize on the peak pressure displacement, the corresponding normalized pressure distribution is calculated. To do so the distance (x) and the pressure component (P) are normalized respectively with the total contact width (W total) and the maximum peak contact pressure (P max). The result is showed in frictionless state (Figure 6.20) and with friction appliance (Figure 6.21).

Effect of friction on the pressure distribution

Figure 6.18: Frictionless static contact pressure at BSA=30°.

Figure 6.19: Static contact pressure at BSA=30° with friction equal to 0.5.

Figure 6.20: Frictionless normalized static contact pressure at BSA=30°.

Figure 6.21: Normalized static contact pressure at BSA=30° with friction equal to 0.5.
On the basis of the simulation, the following hypothesis could be inferred:

- At an equivalent friction level, the behavior for low interference configurations would be more unstable than it would be at high interference, since the peak pressure is likely to move nearly all along the complete contact width. Such an observation could explain the chattering phenomenon that is observed for low interference configuration.

- At high interference configurations, the stress concentration is located close to the blade edge, so that high degradation should occur in this specific area.

In addition to the effect on the contact pressure distribution, the friction will induce some stress variations in the front edge of the blade. Actually, part of the elements that are located on the blade front edge in frictionless state will move into the contact once the friction is applied. As a consequence, these elements will often undergo a large increase in their compressive stress (Figure 6.22).

However, it can be noticed that the tensile stress is increasing for some elements that are just above the contact on the front edge, when friction is applied (Figure 6.23). Internal researches, carried out to understand the wear process on the cleaning blade, identifies that the first crack initiation usually occurs several micrometers above the contact [Thayer]. It is a fatigue wear mode induced by cyclic stress variations. It can be predicted that the amplitude of the variation from compression to tension increases when the friction becomes higher. If the friction becomes extremely high it might even be expected that the material will fracture at the location where the stress bypasses the tensile strength of the material.

Figure 6.22: Variation of the minimum principal stress from frictionless state to friction state ($\mu=0.5$) on the front edge of the blade.

Figure 6.23: Variation of the maximum principal stress from frictionless state to friction state ($\mu=0.5$) on the front edge of the blade.
6.5 Analyzing failed products with the help of physical model

The failure analysis consists in a systematic examination of failed devices to determine the root-cause of the failure. In this step, the failure analysis is designed to identify: (i) the failure modes (the way the product fail), (ii) the failure site (where in the product the failure occurred), (iii) the physical evidences of the failure, (iv) the time-to-failure, (v) the potential conditions that lead to failure.

This step aims at clarifying the field reported problem. It is a combination of interviews with service engineers and a collection of physical evidences, which is needed to provide a clear understanding of the problem. The collection of physical evidences is based on several units, which were sent back from the field for analysis. Thus some hypothesis may be inferred after investigation.

What is the problem?

The more severe form of the failure under investigation results in a complete flip of the blade, which stops the machine. Once the blade is flipped, the torque required to rotate the photoreceptor is too high and results in a hard stop of the driving system.

The other problem results in copy quality defects. Such defects are characterized by an undesirable line or lines distributed randomly on the copy. It is undesirable in the sense that the line is present, when it is not expected (for example a black line on a white page). The line is following the photoreceptor circumference.

Both failures result in customer complaints. The copy quality defect is more susceptible to customer appreciation.

Where is the problem?

The problem is reported by different customers located at different geographical locations.

At the system level, such type of failure occurs on color products with distinctive xerographic modules per color (Black, Cyan, Yellow, and Magenta). The failure is specific to one product. The problem is reported on color xerographic modules: cyan, yellow, and magenta.

At the sub-system level, the blade flip failure necessarily involves the cleaning sub-system. For the copy quality defect, the lines are in fact located on the photoreceptor surface and results from toner bypassing the cleaning blade.
When does it happen?

Such information is not directly available to the design team when the units are analyzed. Currently, only a calendar scale is available, which gives little information in such context. Units can be stored several weeks or even months before they are used so that any correlation with usage time scale is impossible. In order to get further information, interviews with several field engineers were conducted. One should realize that there is no control on the quality of the given information.

Sometimes, the blade flip problem happened just after some new units were inserted in the machine during the first rotations of the xerographic module. It will be called dead-on-arrival units. Sometimes, the failure happens after 2,000-10,000 drum cycles, which represents five percents of the specified life. Copy quality defects are reported in the same range of cycles.

Is there physical evidence?

As the failure seems to pinpoint deficiency in the cleaning sub-system, careful observation of the photoreceptor and the cleaning blade are carried out.

The drum photoreceptor surface is not showing any particular degradation. For copy quality defects, some lines of toner come along the photoreceptor surface. The toner particles are not sticking to the photoreceptor so that they can be removed relatively easily. Once the toner is wiped-off, the drum surface is still intact. No scratch-abrasive pattern appears on the surface along its circumference. Experience on past products confirms that abrasive wear results in very distinctive patterns on the photoreceptor. Therefore, such an observation leads to reject a failure driven by abrasive particles.

The blade observation gives more insight. Some wear patterns are observed on the rubber blade, but there are localized at different spots along the blade length. The wear observation on microscope distinguishes three patterns:

- “Scars localized on the front edge” are mainly observed above the contact edge at a distance of several hundreds micrometers. According to the analytical finite element model, the position of a scar at this location implies the effect of important friction. (Figure 6.24).

- “Cracks localized on the front edge” are mainly observed above the contact edge at a distance in the range of half-hundred micrometers. The material has been submitted to a stress that is higher than its stress resistance leading to its fracture (Figure 6.25).

- “Wear localized on the blade edge” are mostly observed at the blade edge. Some pieces of rubber have been completely removed (Figure 6.26).
As the “usage time” is unknown, it is difficult to know in which sequences all these events and consequently wear patterns are occurring. However, some of the units with a blade flip; a single scar is sometimes noticeable on the front edge. In other cases, these three patterns can be observed on the same blade at different locations. The size oscillates from several millimeters until several centimeters. The patterns are not observed at recurrent locations from one unit to another. The patterns are randomly distributed along the blade length. Moreover, the contact area is not showing any wear. It should be noticed that units that reach end of life without complaint have been also observed for comparison and they do not show such defects. Similar remarks can be made on other products. Based on historical data and current products on the market, severe wear patterns like these ones have never been observed, even when they have run a much larger number of cycles (up to fifty times more).

The analysis of the units should now be related to the different conceptual models for failure defined by [Dasgupta&Pecht1991]. Four models have been specified:

- **Stress & strength model**: The item fails if and only if the stress exceeds the strength. A non failed item is good as new: if the stress does not exceed the strength, the stress has no permanent effect on the item,

- **Damage & endurance**: a stress that causes damage that accumulates irreversibly as in fatigue and wear phenomena. The accumulated damage does not disappear when the stresses are removed,

- **Challenge response**: an element of the system is bad, but only when the element is challenged (needed) does it fail to respond, reveal itself as bad, and cause the system to fail,

- **Tolerance requirement**: a system performance characteristic is satisfactory if and only if its tolerance remains within requirement, i.e., failure occurs when something is nominally working, but not well enough.

According to the first observations made, the following conceptual model and failure mechanism could be applied (Table 6.3):

**Table 6.3: Potential failure mechanism acting on the field failed item.**

<table>
<thead>
<tr>
<th>System Failure</th>
<th>Wear pattern</th>
<th>Conceptual failure model</th>
<th>Failure mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Flip</td>
<td>Scar front edge</td>
<td>Stress &amp; Strength</td>
<td>Overstress</td>
</tr>
<tr>
<td>Copy quality</td>
<td>Crack front edge</td>
<td>Damage &amp; Endurance</td>
<td>Overstress</td>
</tr>
<tr>
<td>Copy quality</td>
<td>Wear localized edge</td>
<td>Damage &amp; endurance</td>
<td>Wear Out</td>
</tr>
</tbody>
</table>

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Figure 6.24: Scar on the blade front edge (1 sub-division = 10 micrometers).

Figure 6.25: Crack on the blade front edge (1 sub-division = 5 micrometers).
Figure 6.26: Wear at the blade edge (1 sub-division = 5 micrometers).

Figure 6.27: Localization of the different wear patterns on the blade.

Zone A: Scar on the front edge (150-250 micrometer above the contact)
Zone B: Crack on the front edge (50-75 micrometer above the contact)
Zone C: Wear on the blade edge (Intersection contact-front edge)
6.6 Conclusion on the analysis of individual field failures

The sub-system under investigation is described by the physics of tribology. The nature of the interactions that take place at the moving interface controls its friction, wear and lubrication behavior. Academic research provides a lot of analytical and empirical models that describe the lubrication regime in a contact, the friction between two bodies, and the wear mechanisms. However, in an industrial context, the design optimization based on an in-depth study of each single model is not conceivable. It would quickly lead to a large scope of potential failure mechanisms to be studied, without prioritization. In such a context, a preliminary analysis of the field failed units is required. It guides the selection of an appropriate physical model to understand the field failures. These activities have been carried out, and enable some preliminary conclusions.

The analysis of failed units from the field confirms that there is a class of failures occurring far earlier than in the rest of the population. Physical evidence supports the sub-population classification: specific wear patterns are observed on these units. However, they are not noticed on products currently on the market that reach far longer life (either from the same product family or from other products families). According to the physics-of-failure, several models for failure are likely to occur on systems: stress-strength, damage-endurance, challenge response, and tolerance requirement. The wear pattern analysis tends to show a preference for the stress-strength and damage-endurance conceptual failure models. The position of the wear pattern on the cleaning blade front edge seems to imply the effect of friction.

For this reason, a good understanding of the cleaning sub-system design parameters is required. Currently, the operational cleaning window is defined through the use of two parameters: blade load and working angle. It was considered that such parameters were not sufficient to describe accurately the contact between the blade and the drum. For this purpose, an analytical model using finite element method has been developed to assess the contribution of the cleaning subsystem design parameters and to achieve a better description of the contact pressure distribution. The contact pressure distribution is itself characterized by several attributes: the contact width, the maximum contact peak pressure, and the pressure gradient. Therefore, it suggests that a refined operational window should be built according to these three attributes. Their impact on the cleaning efficiency performance and reliability should be more deeply studied.

In addition, under operational conditions, it is likely that fluctuations in the coefficient of friction between the photoreceptor and the cleaning blade occur. The effect of friction and the effect of the cleaning design parameters that influence the pressure profile have been also investigated using the finite element model.
The most important conclusions are as follows:

- The smaller becomes the contact width, the higher is the maximum peak pressure in the contact. Thus, cleaning efficiency should be theoretically improved. However, the cleaning efficiency might be jeopardized once friction acts on the cleaning subsystem. Effectively, the simulation indicates that the peak pressure shifts towards the trail of the contact width once friction is applied. Thus, variations in friction might lead to instability within the contact so that the peak pressure is able to move all along the blade width. As a consequence, such configuration should also be more likely to flip if such a phenomenon is friction-driven.

- The larger becomes the contact width; the lower is the maximum peak pressure in the contact.

Accordingly, the pressure profile has a flat shape, which leads to poor cleaning efficiency. With respect to friction, the increase in peak pressure is essentially concentrated in the front of the contact width. At equivalent friction, the peak pressure displacement within the contact is much less important at large contact area than at small contact area. Thus, for such configurations, the lack of lubrication should lead to damage concentrated on the blade edge.

- The friction also contributes to important stress variations in the blade front edge.

A large increase in compressive stress for the material that moves from the front edge to the contact is observed. A stress variation from compression to tension for the material that remains just above the contact once friction is applied is highlighted. Such effects are proportional to the friction level. If the tensile stress goes beyond the material strength resistance, cracks are likely to appear.

The finite element model highlights the variations that might be expected in the contact pressure distribution in function of the design parameters and of the coefficient of friction. The correlation between the analysis of failed units and the analytical model seems to pinpoint a friction driven failure mechanism so that the friction level might be the stress factor.

In this chapter, the analysis of the field failed units and the use of analytical models help to select the most likely failure mechanism that leads to this specific field failure. In the next chapter, the root-causes of the failure have to be found. Early wear-out failures usually arise either from product variability (e.g. flaw in material induced by manufacturing process) or from variability in customer use (the design is not robust enough in such conditions), or from an interaction of both. Thus, a comparative study from product to product is conducted so that differentiation in design, customer profile, and manufacturing process between products is highlighted. This approach should assess the impact they might have on the failure mechanism.
On such a basis, inputs/parameters for the experiments are selected and experimental works are carried out to trigger such a stress. The controlled conditions in which tests are performed intend to demonstrate the reproducibility of the failure mechanism seen in the field. They will also provide insight into the chain of events that lead to the failure, the time to failure, and the root-cause of the failure.
Chapter Seven: The use of guided experiments to reproduce field failure and to enable root-cause analysis

The previous chapter identifies the more likely failure mechanism that lead to the studied failure. In this chapter, some experiments are run in controlled conditions and they aim at reproducing at the design level the field failures. It is demonstrated that failure of class one and two can be reproduced so that the conditions that lead to the failure are determined. Therefore, the failure is predictable and the design parameters that need to be optimized are identified.

7.1 Introduction

In the previous section, a certain number of interactions and possible failure mechanisms that might occur on two contacting bodies have been highlighted. In order to narrow the scope of the analysis, it is advised to focus on failure modes occurring on existing products in the field. The experimental process aims at understanding why and how individual failure mechanisms are occurring. In this chapter, the experiments are conducted under controlled conditions. They should succeed to reproduce at the design level the failure modes as seen in the field.

The potential number of parameters involved in the failure mechanism is currently very large. In order to fully benefit from the experiments method, this number of parameters should be limited. A guided selection is thus required and is described in section 7.2. Once the selection is achieved, the experimental set-up can be designed. The required equipment is described in section 7.3. Then experiments are carried out and the results are given in section 7.4. In section 7.5, the root-cause analysis is performed. Finally, conclusions from the experiments are drawn in section 7.6.

7.2 The selection of parameters

The experiment strategy seems the most appropriate to tackle the current situation. An experiment is the most suitable type of research for gaining experience with newly created situations or processes [Verschuren & Doorewaard 1999]. An experiment is characterized by the following criteria: control the choice of the parameters, control the level of the parameters, perform the experiments on a random manner, and limit the outside influence (i.e. reduce noise).
The experiment process consists in three main steps:

- Select a set of parameters and their levels
- Run the experiment
- Analyze the results

In order to proceed through a structured approach, the parameter selection is conducted along three axes:

- A choice of the potential factors that lead to the failure is established based on product knowledge,
- A correlation between factors and conceptual failure mechanism.
- A comparative study is carried out that consists in comparing failed products and non-failed products from the same product family (i.e. potential variability in manufacturing process and design), and in comparing products of different families (i.e. potential difference in manufacturing process and design).

Therefore, a list of potential factors that lead to the failure mode is built-up. The list is classified according to four categories: manufacturing, environment, machine, and design (Figure 7.2). These categories are adapted from the classical cause and effect diagram developed by [Ishikawa1988]. For each category, the relevance of selecting the parameter is given.

### 7.2.1 Parameters related to the manufacturing category

**Photoreceptor/toner/blade process**

1. Process newness

The toner, blade and photoreceptor manufacturing process are similar to processes used on other products currently on the market. No radical change is involved in any of these processes.

2. Traceability

All these processes generate components/items in the form of batch. Every component is identified by a serial number, which allows its tracking up to its production date and batch number (e.g. blades cut from the same sheet of material are identifiable). Accordingly, it is expected that a failure mode associated with one of the processes should lead to “epidemic” failures assuming batch contamination. Furthermore, statistical controls bearing on manufacturing processes are implemented to monitor variability in the processes, so that correlations between process variability and production date can be drawn.
The analysis conducted in the course of the research outlines that none of the available data (units which have been investigated at the design level) is showing reciprocal relation between failure and production date/batch number. Thus field data does not show evidence that the failure is strictly attributed to variation in the manufacturing process of photoreceptor, toner or blade. Furthermore such failure has never been observed on any other product. As a consequence the blade, drum and toner processes do not testify that they are implied in the failure mechanism.

**PMMA lubricant application process**

The purpose of the PMMA process is to provide initial lubrication to the cleaning system. The process has a high interaction with the cleaning subsystem.

1. **Process newness**

Indeed, the design team initially considered the PMMA process as a root cause for the failure under investigation (i.e. blade flip). Thus, one important modification has been made to the PMMA process: the initial manual application process has been replaced by an automatic application process. After such a modification, a decrease in the number of field failures has been clearly observed. Nevertheless, the implementation of an automated manufacturing process was not sufficient to eradicate the failures, since field failures are still reported.

![Figure 7.2: Cause and effect diagram for cleaning sub-system failure.](image-url)
2. Traceability

The PMMA process is not as traceable as the other process in the sense that no physical measurement is made to attest its quality. Its quality is validated only through visual inspection. Such process is susceptible to unit to unit variation, and even within unit variation.

The analysis of failed units showed that several units that have been sent back by service engineers have been assembled at the same date. In such context, the hypothesis that the PMMA process might be involved in the failure mechanism is founded. However, the same process is currently in use for other products (i.e. other product family) where the failure under investigation never occurred. Thus, it is unlikely that the process is alone responsible for the failure, but it could be the results of interaction phenomena. Thus the lubrication with PMMA is a factor to take into consideration for the experiments.

Module assembly

During the inspection, no particular sign of mistakes that could occur during the assembly process has been noticed. Therefore, this factor was not investigated further.

Transport

The failure under study has been only observed on one product whereas the same kind of transport is used for all products. In addition, tests are carried out in the product development process to simulate transport/handling conditions but the tests did not reveal the failure. At a first instance, this parameter has not been inquired.

7.2.2 Parameters related to the environment category

During the validation and verification tests, some environmental tests are performed. No failure was observed during the testing phase. As such failure type has never been reported from other products neither; it is assumed that there is no clear sign that the environment is only responsible of the failure. In addition no remark from service engineers addressed directly a correlation between customer running in specific environmental conditions and the failure. However, there is no registration of temperature and humidity embedded within the cartridge, so that it is impossible to estimate the contribution of environmental conditions in the field.

Thus at a first instance, environmental conditions are not tested, but they will be controlled to avoid noise in the experimental phase.

7.2.3 Parameters related to the design category

1. Toner/drum/blade material properties

The goal is to reproduce the field failure with materials, which are actually used on current products. Therefore, the blade, drum and toner properties are considered as given.
Furthermore, the blade, drum and toner properties cannot be easily customized so that each single material property can be separately adjusted to a desired level.

Taking into consideration the complexity of such factors, their levels are not changed.

2. Blade design

The design settings of the cleaning sub-system in the investigated product are slightly different than the settings of other products (i.e. other product family). In particular, the blade interference is low in comparison to other products. Even if the latitude window was validated during the design phase of the product, the contribution of the cleaning-subsystem settings is unknown under failure conditions. In addition, the simulations made with the finite element model stress a significant effect of blade settings on the contact pressure distribution.

Thus, the blade interference should therefore be considered in the experimental phase.

7.2.4 Parameters related to the machine category

1. Setting

The service engineers did not underline a specific setting on the machine that could explain the failure mechanism. No further action has been followed.

1. Maintenance

The fact that failure is strictly induced by maintenance or repair from the field is not reckoned. The service engineer confirmed that the failed units were coming directly from the manufacturing site. Nevertheless, considering the direct implication of service engineer in the maintenance program, it is not inconceivable that the information is to a small degree hidden. Unfortunately, this information is extremely difficult to check.

2. Customer use

The machine design makes the cleaning system very dependent on the customer for lubrication because the main source of lubrication is the toner. The amount of toner left on the photoreceptor varies according to the type of document made by the customer. Documents, with a very asymmetric copy pattern or very low toner area coverage, lead to poor lubrication for the cleaning system. The service engineers confirm such information: the failure is observed at recurrent customer places and at customers using similar kind of documents.

As it was highlighted in the previous section, the lack of lubrication for solid contacts might lead to severe wear or high coefficient of friction. Investigation on several units from the field shows excessive degradation-wear at localized positions along the blade, which accentuates the belief that friction is involved in the failure mechanism.
In addition to the friction level, another contribution might come from the length of the job run by customers. In such context, the term length refers to the number of cycles made in a row without interruption. Friction phenomena involve heat dissipation. A long job is expected to be more stressful due to the accumulation of heat at the interface blade drum, in particular in poor lubrication conditions. An excessive temperature might locally change the material property that finally accelerates the blade material degradation. As rubber materials are known to have poor thermal conductivity properties, such a phenomenon is not unlikely. In opposition, the short cycle job should allow a decrease in the temperature interface since the process will stop for a certain time.

Thus, the customer use-profile in interaction with the type of job is considered as an important factor to take into account for the experiments.

3. Xerographic process speed

The process speed influences also the heat dissipation in the contact. In a sliding contact, the dissipation of temperature is directly proportional to the speed difference between the two bodies [Jaeger1942]. Thus, there is a potential risk that the temperature will induce instability in the system. An increase in temperature might influence friction or wear resistance of the rubber.

7.2.5 Conclusion related to the selection of the parameters

The information gathered from the field is translated into parameters and levels. The field information gives a strong signal that the failure is driven by a certain usage of the machine. Thus the objective is to understand how such customer profile influences our system. From the tribology point of view, one key element driven by the customer is the amount of lubrication provided to the system. So a plausible hypothesis is that the failure is driven by a lack of lubrication resulting in a high friction level between the photoreceptor and the blade. The best approach to simulate this extreme behavior is to keep the system in dry-condition. It is achieved by providing an initial amount of lubrication to the system without changing these conditions once the system is running. The initial amount of lubrication is provided through the PMMA powder. Two levels are actually chosen for this parameter: “appliance of PMMA” and “no appliance of PMMA”. By doing so, different initial friction conditions are simulated.

In addition to the direct stress (load) induced by the lubrication level, the job type and xerographic speed can also act upon as thermal stress to stimulate overstress or wear-out failure mechanism. For this purpose, the xerographic process speed is set to two levels: “high” corresponds to high speed, and “low” corresponds to low speed. The job type is set to two levels: “high” corresponds to long job, and “low” corresponds to short job.
7.3 The experimental set-up

In the experimental process, one of the requirements is to minimize the uncontrolled-noise in the course of the experiments. For this purpose, it is advised to limit the experimental set-up to the required equipment to simulate the failure under study. By doing so, interaction phenomena are largely reduced. Attention should be given to the build-up of tools that enable accurate control on the critical parameters selected for the tests.

As it was explained in the previous chapter, the cleaning sub-system is a process within the xerographic module, which interacts with other modules to constitute a complete machine (Figure 6.1). In a machine, the potential interaction of one module with other modules cannot be ruled out. During the experiments, the process that is under investigation has to be isolated from the rest of the machine. Otherwise, uncontrolled interactions might occur and perturb the experiments. Moreover, the current field information analysis does not lead to the conclusion that interaction with other modules could be involved in the system failure. Consequently, a first step is to build a test-bench with those parts that fit the need for the experiments.

The test-bench has the capability to drive the photoreceptor, to insert normal cartridges as well as a customized cartridge (described below), to select several process speeds, to perform different types of jobs (Figure 7.3). The test-bench is controlled by a lab view software interface. Even if the experimental set-up is optimized to avoid uncontrollable interactions with other modules, few modifications have been made to the hardware to keep close correlation with a real machine in terms of dynamic and inertia.

![Figure 7.3: The test bench.](image-url)
In order to explore the complete cleaning operation window (blade load and working angle), the cleaning sub-system design settings/parameters need to be modifiable. Experience from internal tests notifies the importance of these critical parameters. The finite element model showed the large difference in the pressure distribution once the parameters are changed. Therefore a customized cartridge, which gives the ability to play with different blade settings, is designed (Figure 7.4). The tool is built to explore a cleaning latitude window that is larger than the current product specification.

The blade tip position is controlled through the use of a micrometer spindle, which enables displacements along the (x, y) axis. By doing so, the blade interference and the blade setting angle are changeable. The micrometer spindle has a precision of ten micrometers. The tool gives the freedom to set the blade interference and the blade setting angle well beyond the current product specification, with a very good reproducibility.

Figure 7.4: Cleaning sub-system design tool
7.4 The experiments

The purpose of the experiments is to replicate the field failures at the design level. The experiments should confirm that the same failure mechanism as seen in the field is reproduced. The test strategy is failure oriented. The purpose is to highlight design weaknesses, and to explore the system behavior beyond specification.

As a consequence, one step is deliberately skipped in comparison to the conventional procedure during the assembly process: the print test. Such test, which validates the quality of the assembly process, is providing in the mean time toner lubrication to the cleaning-subsystem. At this stage, the experiments are conducted on purpose without toner lubrication.

7.4.1 The first set of experiments

The methodology used to generate the test matrix for the experiments is a full factorial design of experiments method. The full factorial is a pure method; it neatly separates main effects and their interaction effects, compartmentalizing all second order, third order, and even higher order interaction effects [Bhote1999]. The results are separated in two categories. The flip column corresponds to the flip failure mechanism: if such a failure occurs, the test is immediately stopped. If the system does not fail through blade flip mechanism, the test is stopped after a certain amount of cycles that corresponds to five percent of the system life specification. Then a test is made to judge the cleaning efficiency: cleaning efficiency test (CET). The cleaning efficiency is visually evaluated: If the toner bypasses the cleaning blade and results in lines on the photoreceptor surface, the test is considered as failed.

The first series of experiments that has been run to reproduce the failure leads to the following matrix (Table 7.1):

<table>
<thead>
<tr>
<th>Run</th>
<th>Lubrication</th>
<th>Speed</th>
<th>Job type</th>
<th>Flip 1st result</th>
<th>CET 1st result</th>
<th>Flip 2nd result</th>
<th>CET 2nd result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No PMMA</td>
<td>High Speed</td>
<td>Short Job</td>
<td>Failed</td>
<td>Failed</td>
<td>Failed</td>
<td>Failed</td>
</tr>
<tr>
<td>2</td>
<td>No PMMA</td>
<td>High Speed</td>
<td>Long Job</td>
<td>Failed</td>
<td>Failed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>No PMMA</td>
<td>Low Speed</td>
<td>Short Job</td>
<td>Failed</td>
<td></td>
<td>Failed</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>No PMMA</td>
<td>Low Speed</td>
<td>Long Job</td>
<td>Failed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>PMMA</td>
<td>High Speed</td>
<td>Short Job</td>
<td>No Failure</td>
<td>Failed</td>
<td>No Failure</td>
<td>Failed</td>
</tr>
<tr>
<td>6</td>
<td>PMMA</td>
<td>High Speed</td>
<td>Long Job</td>
<td>No Failure</td>
<td>Failed</td>
<td>No Failure</td>
<td>Failed</td>
</tr>
<tr>
<td>7</td>
<td>PMMA</td>
<td>Low Speed</td>
<td>Short Job</td>
<td>No Failure</td>
<td>Failed</td>
<td>No Failure</td>
<td>Failed</td>
</tr>
<tr>
<td>8</td>
<td>PMMA</td>
<td>Low Speed</td>
<td>Long Job</td>
<td>No Failure</td>
<td>Failed</td>
<td>No Failure</td>
<td>Failed</td>
</tr>
</tbody>
</table>

The following observations may be made:

Flip failure

The parameter PMMA gives a strong signal. When the level is “No PMMA”, there is a failure. The second series of tests leads to the same results. However, there is a slight
difference with the failure observed in the field. During this test, all the units fail during the two first cycles. It could also be called “dead on arrival” failure (DOA). After communication with service engineers, it was confirmed that the DOA failure mechanism was observed in the early launch of the product when the process used to apply the PMMA was made manually. Since the process has been changed to an automatic process, such type of failure was reported to a minor level.

The wear pattern analysis on DOA blades resulting from the experiment confirms that the pattern was not in line with the observations on field failed units. Effectively, the DOA unit does not show any wear pattern. But the experiment confirms that the high adhesion between the blade and the drum is undesirable and leads to automatic failure.

The main root-causes that are involved in the automatic flip are directly linked to the manufacturing process. The visual inspection might not be carefully made so that the blade is not entirely covered with the PMMA powder. Furthermore, the transport between manufacturing and customer site might flake the PMMA film. Further action to lean such process reveals the PMMA flaking off if the settings of the automatic process are not set properly. Consequently, the manual process is much more susceptible to such phenomena due to higher variability in the layer deposition.

Cleaning efficiency test

However, the units that did not fail through the blade flip failure mechanism show some excessive wear degradation. The wear is in some cases only localized, and in other cases largely spread along the blade length. In such tests, the wear pattern is concentrated at the edge and presents similarities with the analysis from the failed field units as shown in the previous chapter (Figure 6.25: picture called wear on the blade edge).

Consequently, the ability to clean is reduced and will result in toner line bypassing the blade during the cleaning efficiency test. However, no attempt to correlate the size of the defect on the blade and the ability to clean has been carried out. In addition, the critical size of a toner line on photoreceptor that results in copy-quality defect is not clearly known.

Therefore, the first set of experiments succeeds to reproduce only one aspect of the failure. Thus, the expected blade-flip failure mode is not yet reproduced but the experimental conditions that tend to simulate extreme customer-use contribute to accelerate the blade degradation are reproduced. Therefore, the validity of the test is confirmed.

7.4.2 The second set of experiments

In the second set of experiments, the choice is made to implement another factor in the test, the blade interference. Effectively, the influence of such parameters on the contact pressure distribution is suspected to have an influence on the failure mechanism. According to the first series of experiments, the level for lubrication “NO PMMA” is considered too severe. It is not worthwhile anymore to use it for our experiments so only one level for the lubrication is considered: initial lubrication with PMMA. The flip
column corresponds to flip failure mechanism: if such failure occurs the test is immediately stopped. If the system does not fail through blade flip mechanism, the test is stopped after a certain amount of cycle that corresponds to five percent of the system life specification. The results from the second set of experiments are shown in table 7.2.

Table 7.2: Results second experiment matrix

<table>
<thead>
<tr>
<th>Run</th>
<th>Parameter A</th>
<th>Parameter B</th>
<th>1st result</th>
<th>2nd result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High speed</td>
<td>Short Job</td>
<td>Failed</td>
<td>No Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(4318 cycles)</td>
<td>(20000 cycles)</td>
</tr>
<tr>
<td>2</td>
<td>High speed</td>
<td>Long Job</td>
<td>Failed</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2689 cycles)</td>
<td>(5225 cycles)</td>
</tr>
<tr>
<td>3</td>
<td>Low speed</td>
<td>Short Job</td>
<td>Failed</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(3452 cycles)</td>
<td>(2257 cycles)</td>
</tr>
<tr>
<td>4</td>
<td>Low speed</td>
<td>Long Job</td>
<td>Failed</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1593 cycles)</td>
<td>(2566 cycles)</td>
</tr>
</tbody>
</table>

The blade flip failure is not longer observed at start-up, but it is observed after a certain amount of cycles, which matches with data reported from the field. In such conditions (low blade interference), the probability to have the blade flip is extremely high. In these conditions, the wear pattern analysis was also showing strong similarities with the field. The two patterns - scar on front edge and crack on front edge - are observable on the blade. The results are in line with data from the field, which indicates that most of the time the failure is occurring during the early life of the product. Unfortunately, direct correlation with field data is not possible because the units that were sent back are not embedded with a cycle or copy count time metric.

7.4.3 The influence of a third body

During the experiments, some motor current curves could be extracted. The motor current reflects the change in friction (energy dissipation) during a run. The shape of the motor current curve shows some steady-state and transient periods. Once the first cycles are passed, the system will generally stay in a steady state for a certain amount of cycles. Then the system enters in a transient period, which leads to different scenarios in both configurations (low interference and high interference):

- Low interference: (i) the friction increases and leads to a blade flip leaving a distinct scar on the front edge (ii) the friction, after a relative small increase, drops, which results in some localized cracks on the blade front edge. (Figure 7.5).

- High interference: (i) the friction increases and stabilizes at a relative high level, which results in important wear on the blades such as the blade edge is completely worn (ii) the friction, after a relative small increase, drops, which results in much less severe wear on the blade such as cracks on the front edge (Figure 7.6).

The interesting phenomenon is the drop in friction observed in the course of a run. As no lubrication is added to the system, it could be expected to see a large increase in friction
so that all systems would show severe wear or eventually result in blade flip. However, in several cases, such scenario did not happen. Once the system is disassembled, some debris forms a line in front of the cleaning blade. This debris, issued from the sliding wear between the blade and the drum, is coming out of the photoreceptor top-layer. The blade observation under microscope shows such debris either in the front of the blade edge or on the trail on the contact. It therefore suggests that the system reaches a second steady-state friction level once a layer of photoreceptor debris is formed. This layer could explain the decrease in friction and the localized wear in some conditions. The layer will act as a protective layer, which prevents wear and friction unless the film breaks. In the brake industry, the effect of such lining bodies is known to largely influence the friction between the disc and the pad [Severin&Dorsch2001].

Figure 7.5: Motor current versus time (cycles) at low interference.
Figure 7.6: Motor current versus time (cycles) at high interference.

7.5 The root-cause analysis

In the present section, the objective is to identify the failure mechanism. For this purpose, an accurate measurement of the physical characteristics that drive the failure mechanism should be monitored in the course of the experiments. It allows a better understanding on the chain of events that are involved in the failure mechanism.

The capability to reproduce the field failure has been demonstrated in the previous section, the following observations have been made:

- The first class of failures (hidden 0 hour failures) is induced by variability in the manufacturing process that deposits the PMMA powder lubricant on the cleaning blade. If the initial lubrication deposition on the blade is not carefully applied, the product failed automatically.

- The second class of failures (early wear-out failures) is induced by a certain usage of the machine that leads to poor lubrication conditions. In these
conditions, the blade is very likely to flip at low interference and is wearing very rapidly at high interference.

As the lubrication is largely involved in the failure mechanism, it seems necessary to find a method to quantify friction in the system during a run.

7.5.1. The choice of a method for measuring friction

In the course of the previous experiments, several observations were already made on the failure mechanism:

- The flip initiation is localized: the wear analysis indicates an area in the range of several millimeters for certain cases. Thus it is required to have a spatial resolution in the order of half a millimeter.

- The flip initiation is hardly predictable. At this stage, failure has been observed to be randomly distributed along the blade length. As the current knowledge on the event is insufficient to forecast the specific location of the failure, the method should be versatile enough to allow measurements on large scale (the complete blade length, which is in the order of three hundred millimeters) as well as on smaller scale (down to several millimeters) if more detailed analysis if required.

- The flip event is sudden. As the event is not presently anticipated, the time-span of the failure is not yet known. A first estimation based on the intensity of the motor current data is that the failure does occur in less than one photoreceptor revolution. It is suggested to have a minimum sampling frequency in the order of one Hertz, which corresponds to one photoreceptor revolution.

Such constraints need to be considered for the choice of the method. Several other requirements should be considered. As the mechanism is a dynamic phenomenon, the preference is to use a non-contact method. Any change in the system stiffness might influence the failure mechanism. On the basis of these considerations, traditional contacting transducers (e.g. strain gage) are not considered.

Among the available techniques that could either enable a vibration or a friction measurement the following ones are suggested:

- Torque measurement: the effect of friction is measured through the resulting variations in the torque. A coefficient of friction can be calculated as the ratio between the tangential force and the normal force.

- Laser measurement: the variations in friction are measured through the resulting displacements or vibrations of the contacting bodies.

- Infra-red measurement: the variations in the temperature originate from variations in the level of friction. Other parameters such as the pressure in the contact influence also the temperature.
1. Torque measurement

In a torque measurement, the principle is to deduce the coefficient of friction from the ratio between the tangential force (deduced from the torque) and the normal force applied to the rotating body. The use of torque for friction measurement has the advantage of being technically easy to implement. However, internal communication confirms that such equipment has poor accuracy to detect vibrations induced by the cleaning blade. The driving system design, which allows a uniform motion of the photoreceptor, is guaranteed through the use of a heavy fly-wheel. With such an inertia, all measurements made on the shaft of the driving system lead to poor resolution since most of the blade vibrations are absorbed by the fly-wheel. Consequently, only large variations in friction are actually captured. However, the benefit of the torque measurement compared to the use of the intensity of motor current measurement is relatively low. As the intensity of the motor current measurement is already on the present experimental set-up, another method would be more appropriate.

2. Laser measurement

In laser measurement, the principle is to measure object displacements. Using the principle of Laser Doppler vibrometry, a non-contact measurement of object vibrations can be achieved and it offers significant advantages over traditional contacting vibration transducers \[\text{Bell2000}\]. The equipment provides either in-plane or out-of-plane displacement measurement capabilities. Most of the equipments have the capability to measure vibrations in a broad range of frequencies (on average from 0.1 Hz to 20 kHz) and also provide a displacement range from 0.1 mm to 75 mm with a high resolution (0.1%). The radial displacement calculation made with the finite element model indicates a displacement in the range of several hundred micrometers for a coefficient of friction between 0.25 and 1. It is large enough to be captured by such a device.

However, the main trouble arises from the difficult access to the cleaning blade when it is inserted in a cartridge. Measurements, which could be achieved either on the front edge (out-of-plane) or on the top of the blade (in-plane), require accurate positioning of the laser beam with regards to the targeted surface, i.e. a perfect normal incidence. Furthermore, the spatial resolution of such a device is limited to small spots (several micrometers), which leads to an insufficient coverage of the expected surface unless several beams are used.

3. Infrared measurement

In infrared measurement, the principle is to measure temperature increases that result from the energy dissipation induced by the frictional contact. Increase in temperature is intrinsically related to the level of friction. The heat due to friction is conducted into the two contiguous bodies, the blade and the drum. Therefore, the measurement of the temperature on one of the two bodies gives a relationship with the level of friction. The thermo-mechanical feedback process due to frictional heating in the sliding system can cause thermo-elastic instability, leading to possible localization of high load and temperature. In other terms, temperature supplies information on the distribution and on
the intensity of the pressure in the contact. As the blade flip is expected to start at a localized zone, it could be highlighted through accurate temperature measurement over the drum length.

Such a method has several advantages.

Firstly, it gives the freedom to do some measurements either on the blade or on the drum. As a difficult access to the blade has been outlined, the measurement on the photoreceptor is a possible alternative since energy dissipation is expected on the two bodies.

Secondly, the equipment provides the capability to work with different spatial resolutions.

Thirdly, the infra-red needs to be coupled with a high speed data acquisition. The minimum sampling frequency is four Hertz, which corresponds to data acquisition every ninety degrees of a drum rotation. The maximum sampling frequency is sixty Hertz, which corresponds to data acquisition every six degrees of a drum rotation.

7.5.2 The experimental set-up using infra-red measurement

The temperature at the interface between the blade and the photoreceptor cannot be measured. Thus, the temperature has to be measured either on the blade or on the photoreceptor surface. The measurement zone needs to be optimized between the respective constraints relating to the camera characteristics and to the physical access to the contacting bodies.

Measurement on the blade could be made at two locations: either on the blade front edge or on the top of the blade.

On the blade front edge, the measurements are difficult to achieve because of two effects:

(i) The blade might be subject to a stick-slip phenomenon, which leads to difficulties in order to maintain a consistent incidence with the targeted surface

(ii) Due to the low thermal-conductivity of the rubber materials, the temperature does not dissipate easily in the blade, so that the observed rise in temperature stays very close to the blade-drum interface.

Thus, the measurement requires the use of the highest resolution and an extreme fine positioning of the camera close to the interface. However, at the interface, the blade might not stay in a very stable position since friction is induced in the phenomenon under investigation. The alternative that consists in measuring the temperature rise on the blade from a top incidence might also lead to poor results, since the temperature increase in the rubber is expected to be located close to the interface. Furthermore, both measurements are hardly achievable due to the complex physical access to the blade once it is inserted in the cartridge.

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Consequently, the temperature should be measured on the drum surface. Nonetheless, the camera should come as close as possible to the contact between the blade and the photoreceptor in order to limited cooling effects due to convection phenomena. The temperature measurement on the photoreceptor is achieved by positioning the camera on the top of the system (Figure 7.7). In such a configuration, temperature profile all along the blade length can be extracted. A measurement close to the blade-drum interface is accomplished.

Figure 7.7: Infra-red camera positioning on the blade-photoreceptor system (Top-view).

7.5.3 Theoretical calculation of temperature rise in the blade drum contact

During sliding, the effect of operating conditions such as load and velocity on friction and wear are frequently manifestations of the effect of temperature rise on the variable under study. The mechanical properties (such as elastic modulus and hardness) and lubricating properties of many materials start to degrade with rise of temperature at the interface, which affects their tribological performance. In the absence of lubricant this heat is conducted into the two sliding members through contact spots.

Several analytical models have been developed to calculate the temperature rise in contacting bodies. Several assumptions are made in such analytical models:

- High stress contact condition (apparent area equal to real area)
- Frictional heating assumed to liberated uniformly over contact
- No loss of heat from the surface

If we have two materials, a certain portion of heat will go in one material and the rest will go into the second material (Figure 7.8). It is taken into consideration through the
partition factor. Since the thermal conductivity of both materials is in the same range, it will be considered that the partition factor (r) is equal to 0.5. This value for the partition factor is an approximation but is sufficient enough to have an accurate order of magnitude for the temperature calculation. As the figure below underlines, one material is in a stationary mode whereas the other one is in sliding. Therefore, the formulas used to calculate the temperature rise in the photoreceptor and in the blade are not similar.

![Diagram of temperature dissipation between two contacting bodies](image)

The model developed by [Jaeger1942] is used hereby to calculate the temperature rise induced by the friction between the blade and the drum.

For the photoreceptor, such model gives the temperature distribution ΔT on the surface of an infinite half space underneath and in the vicinity of a moving homogeneous heat source. The motion is of constant speed \( V \) and the distribution is calculated in the steady-state for a heat source with length 2l in the direction of motion. In the equation (1), q stands for the specific heat flow per area and it depends on the contact pressure (P), the coefficient of friction (\( \mu \)) and the sliding velocity (V). The thermal diffusivity \( a = \lambda / \rho c_p \) is composed by the thermal conductivity \( \lambda \), the density \( \rho \) and the specific heat \( c_p \). \( K_0 \) represents a Bessel function of second kind and zero order. The number L is defined as one half of the Peclet-number, which is used to characterize the temperature distribution for different speeds. The thermal properties from the two bodies, the sliding and the contact characteristics are summarized in the following Table 7.3.

The temperature distribution in the moving body of a constant speed is given by the following formula:
\[ \delta T = \frac{2qa}{\pi \lambda V} \frac{X-L}{X+L} \int e^{-ut} K_0(|u|)du \]

\[ X = \frac{Vx}{2a}, \quad L = \frac{VI}{2a}, \quad q = \mu PV \]

For equation (1), Jaeger developed the approximation:

\[ \delta T = \frac{2qa}{\pi \lambda V} \sqrt{2\pi} (L - X), \quad -L \leq X < L \]

\[ \delta T = \frac{2qa}{\pi \lambda V} \sqrt{2\pi} (\sqrt{L - X} - \sqrt{L + X}), \quad X < -L \]

Table 7.3: Thermal characteristics for the temperature dissipation calculation in the photoreceptor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values Drum</th>
<th>Values Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (V)</td>
<td>m/s</td>
<td>0.36</td>
<td>0</td>
</tr>
<tr>
<td>Density ((\rho))</td>
<td>kg/m(^3)</td>
<td>1190</td>
<td>1160</td>
</tr>
<tr>
<td>Specific heat ((c_p))</td>
<td>(J/kg.C)</td>
<td>1705</td>
<td>2084</td>
</tr>
<tr>
<td>Thermal conductivity ((\lambda))</td>
<td>(W/m.C)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The characteristics of the contact that are used for the calculation have been extracted from the finite element model described in chapter six are shown in table 7.4.

Table 7.4: Contact characteristics extracted from the FEM model for the temperature dissipation calculation in the photoreceptor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values Contact Blade-Drum Low Interference</th>
<th>Values Contact Blade-Drum High Interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (V)</td>
<td>m/s</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Half contact length (l)</td>
<td>m</td>
<td>5e-6</td>
<td>12.5e-6</td>
</tr>
<tr>
<td>Pressure (P)</td>
<td>Pa</td>
<td>2.6e6</td>
<td>2.0e6</td>
</tr>
<tr>
<td>Coefficient friction ((\mu))</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

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The numerical application leads to the following results as shown in figure 7.9:

![Graph showing temperature dissipation](image)

Figure 7.9: Temperature dissipation on the photoreceptor surface induced by the contact with the blade.

### 7.5.4 The experimental results

**The first class of failures: hidden 0 hour failures**

These experiments are carried out to have a better estimation of the risk for failure when some zones without PMMA lubrication are deliberately left on the blade. Such experiments aim to assess the risk induced by poor lubrication deposition during the manufacturing process. For this purpose, some different masks are used to generate “risky zones” that could be located at different locations over the blade length and that have different sizes. With the infra-red device, it is possible to pinpoint precisely the location where the failure initiates so that a correlation between the zone without PMMA and the failure initiation can be highlighted. From the experiments, the following conclusions can be drawn:

- The failure is automatic and the initiation location matches with the “no lubrication zone”
- The failure is independent from the location of the “no lubrication zone”
- The failure is friction-driven, so that a rapid temperature rise is noticed through the infra-red camera, but the dissipation is very quick.
Below a certain size of defect (less than half a centimeter), the failure is not anymore automatic. The next exercise consists in measuring the localized temperature rise that might occur during the sliding of the two bodies (blade and photoreceptor). Later on, a correlation between the temperature rise and the wear pattern can be established.

The second class of failures: early wear-out failures

The following characteristics phases have been observed with the infra-red camera.

The system is in a steady-state stage during a certain period. During this period, a temperature rise is captured but it does not originate from the interaction between the blade and the drum. The temperature rise comes from the bearings that are used to provide smooth rotation between the photoreceptor and the driving system. Therefore, the heat flow starts on the photoreceptor extremities (inboard and outboard) and propagates to the middle of the photoreceptor. The heat cumulates and is stored inside the photoreceptor.

In the transient stage, three distinctive patterns have been captured. They are respectively called hot-spot, local flip, and blade flip. These infra-red patterns can be characterized by their size, their time-span and their consequent wear pattern (Table 7.5).

<table>
<thead>
<tr>
<th>Infra-red pattern</th>
<th>Temperature rise</th>
<th>Size</th>
<th>Time</th>
<th>Wear pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Spot</td>
<td>2 – 10 °C</td>
<td>≈ 5 to 20 mm</td>
<td>30 s to minutes</td>
<td>Degradation Edge</td>
</tr>
<tr>
<td>Local Flip</td>
<td>2 – 5 °C</td>
<td>≈ 5 mm</td>
<td>1 to 5 s</td>
<td>Crack</td>
</tr>
<tr>
<td>Blade Flip</td>
<td>5 – 10 °C</td>
<td>≈ 5 mm</td>
<td>&lt; 0.5 s</td>
<td>Scar Front Edge</td>
</tr>
</tbody>
</table>

The temperature increase might originate from several effects: (i) the heat source is coming closer to the location where the temperature is measured, (ii) the increase in friction leads to a larger dissipation of the temperature, (iii) the increase in pressure induced by the friction leads also to a larger dissipation of the temperature. These combined effects cannot be dissociated in the present experimental set-up.

1. Hot spot patterns

“Hot spot” patterns have been captured on high interference configurations.

The size of the initiation site starts in the same range as the other phenomena, i.e. several millimeters. The particularity of these patterns arises from its tendency to grow with time,
so that the spot width increases. The growing phenomena result probably from a high resistance to the tangential force. The finite element model shows that the high interference configuration presents certain characteristics. In particular, the maximum peak pressure is concentrated close to the blade edge. This suggests that the tangential force required to create a flip should be higher than for low interference configurations. Therefore, it could be that the increase in width requires less energy than the propagation in the rotational direction.

The concentrated pressure leads to a rather important increase in the temperature (up to fifty degrees Celsius). It might contribute to the rapid blade degradation on the edge, so that “hot spot” patterns are characterized by severe degradation on the edge as shown in chapter six (figure 6.25).

In such a phenomenon, a steep increase in the intensity of the motor current (transient phase) is often followed by a phase in which the intensity stabilizes at a very high level and reaches a second steady state level.

Such a physical process results in a temperature profile as illustrated on Figure 7.10: the temperature profiles are extracted at different points in time. The position of the camera is not changed during a measurement, so that the temperature profile measurements are always taken at the same location on the photoreceptor. The temperature is measured along the blade length.

2. Local flip pattern

“Local flip” patterns have been captured on high interference and low interference configurations. As opposed to “hot spot” patterns, they do not grow in width.

The particularity of these patterns is that the temperature profile shows a relative rapid increase in temperature (i.e. in the order of several seconds). Then, the temperature drops to its initial value as measured before the increase.

The wear pattern corresponds to a crack located on the front edge as shown in chapter six (figure 6.24). The sudden drops might be explained by the simultaneous fracture of the material and the rapid “bounce back” of the blade tip. The finite element models showed that the crack in the material might be induced by the increase in the tensile stress that occurs on the front edge when the level of friction is high.

The lack of dynamic (i.e. relative slowness of the blade displacement) or the fracture of the material prevents the blade flip to go to completion. In fact, the fracture of the material probably leads to weak contact stiffness that prevents the reoccurrence of the flip at the same location. Indeed, several local flips have never been observed at the same location. For the same reason, a blade flip initiation has never been observed at the same location where a previous “local flip” occurred. Such phenomena do not result in a specific profile of the intensity of the motor current, but they are usually accompanied by a general increase in the intensity of the motor current. The resulting temperature profile is shown on figure 7.11 below. The conditions of measurement are similar to the previous temperature profile.
Figure 7.10: Temperature profile on drum surface versus time: hot spot phenomena.

Figure 7.11: Temperature profile on drum surface versus time: local flip phenomena.
3. Blade flip pattern

“Blade flip” patterns are occurring on low interference configurations.

The corresponding wear pattern is a scar located on the blade front edge as shown in chapter six (figure 6.23).

The particularity of the “blade flip” pattern is an extremely rapid increase in the temperature (i.e. in the order of several hundred milliseconds), followed by the propagation of the temperature rise along the blade length that results from the propagation of the blade flip. On figure 7.12, the main temperature peak corresponds to the location where the flip initiates. The second peak highlights the flip propagation.

The extreme rapidity of the flip propagation makes it very unpredictable. However, the “local flip” phenomena often precede the blade flip phenomenon. The increase in the intensity of the motor current is a precursor to the blade flip failure.

Consequently, in order to prevent any damage to the blade, a careful look-up on the intensity of the motor current should enable the prevention of important damages to the blade.

![Figure 7.12: Temperature profile on drum surface versus time: blade flip phenomena](image)

Figure 7.12: Temperature profile on drum surface versus time: blade flip phenomena
4. Recommendations to improve the use of infra-red devices for the measurement of friction

The use of an infra-red camera looks promising to measure the friction between the blade and the drum. However, several difficulties have been observed in the course of the experiments. They are summarized below:

- First, a very close access to the heat source is not always achievable. In the present experiments, the objective is to reproduce field failures using the equipment that is as similar as possible to the type of machines used by customers. Thus, the possible modifications to the set up are limited. For future experiments, some modifications should be carried out to enable a closest access to the blade-drum interface.

- Second, difficulties arise from the contact characteristics. A small contact width leads to rapid temperature dissipation on the moving surface (i.e. drum). It is a design constraint that cannot be overlooked. Again, a closer access to the contact should lead to more accurate results.

- Third, the presented results have all been made on the photoreceptor surface. Some tries have been given to make measurement on the blade, but they were unsuccessful because of a difficult physical access to the blade. Further experiments should be considered, they might bring sound insights.

- Fourth, the high reflectivity of the photoreceptor surface renders the positioning of the camera difficult. In certain conditions, the optics of the camera reflects on the surface. Thus, it is not always possible to achieve a perfect normal incidence between the camera and the drum surface. The use of smaller infra-red sensor might be more practical.

- Fifth, the temperature rise measured with the camera is caused by several factors. Their individual contribution cannot be evaluated since they are inter-related: the increase in pressure, the increase in friction, and the displacement of the heat source towards the measurement zone are simultaneously influencing the measured temperature rise. The displacement of the heat source could be ruled out if a displacement of the blade tip is made in the meantime. In fact, it would also characterize the friction level between the blade and the drum.
7.6 Conclusions on the experiments

The experiments were conducted to reproduce at the design level a failure mode that occurs in the field. The experiments succeed to identify the conditions that lead to the class one and class two failures. The different experiments give some insight on the root-cause of the failures, so that adequate design change may be proposed.

Failure class one: manufacturing process

The experiments attest that the process of applying the initial lubrication is not always under control. A non-uniform application of lubrication powder all along the blade length results in automatic failure (first cycle). In the early stage of the product launch, the process was manual, leading to large variability in the deposition from unit to unit. The consequence was mainly dead-on-arrival class of failure. Consequently, an automatic process was implemented. A better yield was achieved, but the variations in the automatic process can still lead to failure.

Therefore, the manufacturing process nowadays has a torque control that is made at the end of the assembly process to prevent such failure to occur at customer site. Such type of failure is not reported anymore from the field.

Failure class two: customer profile

The manufacturing process was considered as the main root-cause for the failure under study. However, the experiments show that the powder application process is not responsible for all failures. A second important factor inherent to the design of the system in interaction with a certain category of customers will lead to a second class of failures. Effectively, the cleaning system is not able to withstand dry running condition. Unfortunately, such a situation might happen once a customer uses the machine in certain conditions. When the system runs in dry-conditions, local increase in friction will occur and result in excessive blade wear. In the worst case, the blade can eventually flip over. Such phenomenon is more likely to occur at low blade interference.

As such a class of failure cannot be prevented by the implementation of a single control of the manufacturing process; some modifications to the design are required to avoid reoccurrence of the failure. The root-cause analysis highlights that some of the phenomena that occur in dry-conditions are very rapid and lead to non-recoverable damage. Some correlations between these phenomena and the intensity of the motor current have been established. It suggests that a careful monitoring of the motor current should be used to prevent their occurrence. In other terms, some design improvements are required to have a working system independent of the customer profile. To do so, some modifications to the design are required, so that the over-stress conditions are avoided.
Chapter Eight: Improvement of the product design

The previous chapter showed success in reproducing at design level the failure occurring in the field. The conditions and the root-causes that lead to the failure mechanism have been identified. To prevent future failures, the system must run in a mode such that the root-cause will not occur. Further experiments are carried out to elaborate such concept. Finally design guidelines to prevent the occurrence of the failures are suggested.

8.1 Introduction

The previous experiments revealed the weaknesses of the cleaning sub-system design, once it is used in an unanticipated manner. In particular, the dry-conditions lead to early degradation of the cleaning sub-system. Consequently, quality and reliability requirements are not met in these conditions. Further experiments will help to provide appropriate design rules to prevent premature failure as it presently occurs. They aim at defining some safety margins to the existing design. Different concepts are suggested to maintain the system under these safety margins. The results are presented in section 8.2.

In section 8.3, the capability of predicting the failure in different contexts is demonstrated. Two cases are illustrated: the failure prediction in the course of the maintenance program and the failure prediction in the case of a new design. The maintenance program is used to prolong the life of the machine. To do so, some parts might be replaced (e.g. blade and drum). These replacements might change the interaction between the two contacting bodies. Therefore, it entails a certain risk with regards to the studied failure. In the course of the research, a new generation of photoreceptors has been developed. As the drum surface characteristics have a significant effect on the level of friction, it makes sense to predict the risk of the studied failure mechanism with this new photoreceptor design.

8.2 Introduction of safety margins for design improvement

This section aims at modifying the existing design so that the product performance is improved. However, these modifications should be worked out using a system approach. It implies that the constraints or the advantages of the other sub-systems should be considered to optimize the design.
The design of the cleaning subsystem presents some weaknesses. An extreme rapid wear is observed when the system is working in poor lubrication conditions. The experiments did show that the blade will even flip over in some configurations, so that the customer is unable to use the machine.

As the phenomenon is friction driven, a reliable system should sustain sufficient lubrication to the blade to avoid increase in friction and its consequences. Presently, one major design constraint is that the lubrication supply is customer-dependent. Accordingly, a system that would be independent of the customer’s profile would be an optimal solution to secure the life of the cleaning subsystem.

As a first instance, the best lubricant remains the toner. Its lubricant properties are demonstrated. Field information confirms that units that run in adequate lubrication conditions reach easily their end of life. This statement holds for products of the same family and for products of different families. It confirms the quality of toner as an effective lubricant.

The use of toner presents several advantages. There is no need to validate another lubricant. The existing development process that deposits the toner can be directly reused. There is no design modification to bring to the existing cleaning subsystem.

However, the idea consisting in providing lubrication using the development process has one disadvantage. It might slow-down the process efficiency of the machine. When the machine is in use by the customer, the delivery of toner is impossible without interruption of the process. Therefore, in order to use the development process, the following questions need to be addressed:

- At what frequency is the supply of lubrication required?
- What signal from the machine can be used to trigger the extra-lubrication?
- What method is the most appropriate to justify the application of extra-lubrication?

The starting point for such a solution is to determine the maximum number of cycles that the system can handle with a certain amount of toner. The initial amount of toner is predefined since print-tests are effectively made on the assembly line to validate the assembly process. The print test provides extra lubrication to the blade and it limits the negative effect of variability in the PMMA lubricant application process.

It was deduced from the previous experiments that the intensity of the motor current gives a reasonable indication of the friction level between the blade and the photoreceptor. The classical curve that could be deduced from the experiments has a characteristic shape as presented in Figure 8.1.

The steady state stage is characterized by a system working under proper lubrication conditions, which contributes to a stable motor regime. When the contact starts starving of lubrication, the motor regime becomes unstable: an increase in the intensity of the
motor current is observed. The transient phase is matching with the apparition of hot spots and local flip that might on a later stage lead to the blade flip. Hence, the principle is to prevent the cleaning-subsystem to reach the critical zone when the effect of friction hazards the life of the cleaning system.

### Figure 8.1: Variation of the intensity of the motor current in function of photoreceptor cycles in dry conditions.

#### 8.2.1 System behavior with initial toner lubrication

Since the previous experiments (i.e. experiments carried out in chapter seven) were conducted only with PMMA powder lubrication, the effect of toner as a lubricant is not known. Therefore, the purpose of the present test is to gain insight into the expected variations in the intensity of the motor current in function of the photoreceptor cycle when the toner and the PMMA lubricant powder are used as initial lubricants.

In this first set of experiments, the extremities of the operational cleaning window (i.e. different blade interferences and blade setting angles) are explored with a predefined amount of lubrication: PMMA lubrication applied on the production line and toner lubrication amount deposited during the print test.

Then, the cartridge is inserted on our test-bench and is run for a predefined amount of cycles without interruption. The predefined amount of cycles is deliberately chosen rather long so that it corresponds to ten percent of the life of existing machines. No extra lubrication is added in the course of the experiments.

The purpose of the tests is to gain insight on the shape of the intensity of the motor current curve in function of the number of photoreceptor cycles. The test is stopped before the end only in two cases: a blade flip or a hard stop of the motor. The motor hard stop results also from an excessive friction.
The results from the experiments lead to the following conclusions.

- The initial amount of toner will not provide sufficient lubrication on the long term and cannot be considered as sufficient to prevent blade flip or excessive blade wear.

- All configurations lead to the same characteristic shape for the intensity of the motor current, so that they present the same potential risk with regards to early-wear out phenomena.

The characteristics of the intensity of the motor current curve show some similarities (Figure 8.2):

- The lack of lubrication leads to a sudden increase in intensity of the motor current.

- The system behavior after the first increase in intensity is difficult to predict: (i) the intensity drops (ii) the intensity stabilizes to a high level (iii) the intensity oscillates.

One possible solution would be to increase the initial amount of lubrication in the perspective of reaching a lubrication level that will be safe even for long term. However, such experiments at different initial lubrication levels did not bring any improvement. The same characteristic curve is always obtained. The hypothesis that the system reaches a saturated lubrication level is very likely.

Figure 8.2: Intensity of the motor current versus drum cycles with initial toner lubrication.
8.2.2 Different solutions to avoid the failure occurrence

The experiments confirm that the system is not robust enough to withstand long dry conditions even with initial extra-lubrication. It is thus required to develop a method to provide lubrication when the lack of lubrication induces substantial risk for the system. The next question is: on which basis should the extra-lubrication be applied?

Several concepts are suggested as potential solutions.

1. The threshold principle

The “threshold” method consists in defining in advance an upper boundary value for the intensity of the motor current, so that some lubrication is provided to the blade as soon as the measured intensity goes beyond this value. It is a control-loop mechanism.

Attention should be given to one aspect: different blade loads correspond to different nominal values for the intensity of the motor current when it runs in a normal regime. The spread in load within specification should be carefully considered: the latitude is reduced at higher load if the same-upper value is used for all configurations (Figure 8.3). The application of wrong settings will lead to situations where the extra-lubrication is always triggered. Moreover, it is not really obvious that the system is prone to failure above a certain intensity of the motor current.

![Threshold principle diagram]

Figure 8.3: Threshold principle.
2. The “average safe cycle” principle

Such a solution is based on calculation of an average number of cycles that the system can stand with a defined amount of toner. It requires an accurate statistical analysis to determine with a sufficient confidence the “average safe cycle”. However, it is an open-loop control mode that presents several inconveniences. It will react independently of the real state of the sliding contact:

- Some toner might be dispatched even if the system is still in a steady-state stage, which is not a cost effective solution.

- An increase in the level of friction might happen before the assigned value for lubrication dispatching, with the system not being able to react with a corrective action.

3. The “motor current slope” principle

Such a close-loop control system is based on a continuous calculation of the intensity of the motor current so that its variations are captured. The tests highlight rapid and steep increase in the intensity of the motor current once the system starts to be unstable so that some characteristics slope can be identified. As a consequence, minor variations can be neglected. Only distinctive slopes are actually followed by deposition of extra-lubrication. Such a method is not susceptible to blade load variations from one unit to another. Moreover, it is a real system response control-loop mode. The system is activated only when it is required. The three concepts are summarized in Figure 8.4.

![Figure 8.4: Different concepts for safe system and add extra-lubrication.](image-url)
8.3 Risk evaluation of the studied failure mode in different contexts

As the conditions that lead to the failure have been identified, the risk of occurrence of the failure in the different phases of the product life cycle can be assessed. Two situations are particularly interesting to study. The first one is the maintenance phase where the information available to the design team is difficult to verify as all the actions are carried out by the service organization. The second one is when a new product using an evolutionary design is developed. In this case, early risk prediction is possible. By doing so the efficiency of the learning-cycle is demonstrated.

8.3.1 Risk evaluation of the failure during maintenance program

Most of the products are likely to be under a maintenance program. During the repair action, the two items (blade and photoreceptor) might be changed independently. The failure mechanism under investigation involves contact bodies, where the contribution of the surface might be considerable. Therefore, in the next set of experiments, an estimation of the risk for different configurations is carried out. The experiments are run in the same conditions as in the previous set (PMMA and toner are used as lubricant). The following matrix is built-up to investigate the effect of aged bodies on the failure mechanism:

<table>
<thead>
<tr>
<th>New Blade</th>
<th>New Blade/New Drum</th>
<th>New Blade/Old Drum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Blade</td>
<td>Old Blade/New Drum</td>
<td>Old Blade/Old Drum</td>
</tr>
</tbody>
</table>

For the category “old”, the blades and drums are taken randomly from units that came back from the field. In figure 8.5, the intensity of the motor current in function of the number of photoreceptor cycles is displayed for each of the experimental cases.

Old blade / Old drum configuration

This set of experiments brings new insight into the failure mechanism. First, the result that is obtained with old-blade and old-drum configurations, tends to corroborate the field information that the failure mechanism under study does not occur on products once they bypass a certain number of cycles. It is noticeable that the intensity of the motor current is very stable and stays to a relative low level. In particular, the level of friction seems to reach a steady-state level that is not disturbed by the lack of lubrication. Even if the sensitivity of the motor current is too coarse to conclude that there is no local change in friction along the blade length, the amplitude of these variations is much less important than on new sub-systems.
Figure 8.5: Motor current versus photoreceptor cycles. Upper left: new blade-new drum; Upper right: new blade-old drum; Lower left: old blade-new drum; Lower right: old blade-old drum.

It would suggest that the blade wear is dominated by other failure mechanisms, probably like abrasion and/or fatigue, if the transition from new to old drum surface is made smoothly. In addition, the microscopic analysis of the units (old-old) does not present any wear pattern as presented in the previous chapter.

In this context, the change in the surface state of the photoreceptor could explain the large difference in wear pattern between end-of-life products and products that failed through the blade flip phenomena. In particular, the lack of lubrication does not have the same impact if the parts are brand new or old.

New drum / Old blade configuration

This experiment shows an interesting behavior. The system is as unstable as in a new drum-new blade configuration. It implies that the drum surface seems to bring a dominant contribution into the level of friction. In particular, the experiment new blade-old drum leads to a very stable level of friction. Consequently, a certain transition in the surface state of the photoreceptor is required before the level of friction becomes stable. However, such a transition might jeopardize the cleaning-subsystem life.

In literature, such phenomenon is called “running-in”. “Running in” concerns tribological transition, in wear and in friction, which are observed shortly after the start of a sliding
contact between fresh and unworn solid contacts. [Blau2005] defines frictional running-in according to three attributes: (i) the duration of certain characteristics transients within the running-in period, including the time to reach steady-state, (ii) the general trend (shape) of the friction force versus time of operation, (iii) the instantaneous level of friction fluctuations superimposed upon the general trend. [Blau2005] outlines that changes in friction and wear that occur during running-in can be a consequence of surface roughness alteration, change in surface composition, microstructure, and third body distribution.

These effects are in line with the observations made with the third body as presented in the section 7.4.3. It would also suggest that the drum maintenance entails potential risk. On this point, no remark has been reported from the field.

8.3.2 Risk evaluation of the failure with a new design

Since the development team has been working on a new generation of photoreceptor, a chance is given to predict the risk associated with the new photoreceptor design. The new photoreceptor coating is expected to have a lower wear rate than the previous design. For this purpose, a new formulation has been chosen: it contains PolyTetraFluoroEthylene (PTFE) fillers. PTFE is known to exhibit very low coefficient of friction [Bhushan&Gupta1991]. The singular PTFE properties originate from: (i) a very low adhesion of the PTFE surface (ii) the easy transfer from PTFE material onto the sliding partner, which results in the formation of a thin film between the contacting surfaces [Lancaster1973] [Tanaka1973].

Therefore, the same series of experiments have been carried out using a PTFE coated drum.

Prediction failure of class one

Some experiments have been carried out to predict the failure induced by a bad application of PMMA. To do so, experiments with a zone intentionally without PMMA have been prepared. Such conditions intend to simulate the most extreme variations in the PMMA process application.

In such a configuration, the risk for failure is as large as for the previous type of photoreceptor coating. It is a one hundred percent chance of failures that occurs on the first cycle. The low adhesion characteristics of the PTFE photoreceptor coating are not sufficient to prevent the occurrence of such a failure. Consequently, the manufacturing process still entails a large risk with regards to this class of failures (class one failure).

Prediction failure of class two

The second class of failure is tested in the conditions: initial lubrication with PMMA lubricant powder and toner lubrication. The results do present a large improvement with regards to friction. The friction remains low and stable.
There are no noticeable variations in the level of friction. It suggests that the cleaning system is not anymore dependent of the lubrication level. The microscopic analysis of the blade does not show any wear pattern as it was usually observed with the other type of coating.

This behavior could be explained by the rapid formation of a thin film between the blade and the drum that reduces the friction and prevents excessive wear. Of course, the low friction properties of PTFE material might also contribute to this behavior. Consequently, the new type of coating is a significant improvement in terms of friction. The failure mechanism under study is not reproducible with such a type of photoreceptor coating. It is confirmed even for a blade working at low interference that was previously susceptible to blade flip phenomena (Figure 8.6).

Figure 8.6: Comparison test between conventional photoreceptor coatings and new PTFE coating for new blade.

*Upper left:* New Blade - Conventional Coating - Low Interference;
*Upper right:* New Blade - Conventional Coating - High Interference;
*Lower left:* New Blade - PTFE coating - Low Interference;
*Lower right:* New Blade - PTFE coating - High Interference.
8.4 Summary of the experiments

The following table summarizes the counter measures that have been undertaken to tackle class I and II failures, and give recommendations for analyzing class III and IV.

<table>
<thead>
<tr>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Mode</td>
<td>Blade Flip</td>
<td>Hot Spot, Local Flip, Blade Flip</td>
<td>Scratches on drum surface</td>
</tr>
<tr>
<td>Time to Failure</td>
<td>Dead on Arrival (0 cycles)</td>
<td>$\approx 2$ to $8$ k-cycles</td>
<td>$\approx 50K$-$400$ k-cycles</td>
</tr>
<tr>
<td>Root-Cause</td>
<td>High Adhesion between blade-drum induced by variability in the lubricant application process during manufacturing</td>
<td>High friction in low lubrication conditions induced by customer profile</td>
<td>Abrasive particles are trapped between blade and drum</td>
</tr>
<tr>
<td>Counter Measures</td>
<td>• Improve application process</td>
<td>• Additional lubrication triggered by monitoring of the intensity of the motor current</td>
<td>Not studied in this thesis</td>
</tr>
<tr>
<td></td>
<td>• Torque control after assembly process (Go/No go)</td>
<td>• New photoreceptor coating presents no risk with respect to this failure</td>
<td>Further research should focus on the development of a physics-of-failure model to better understand abrasive wear,</td>
</tr>
<tr>
<td></td>
<td>• Guideline to service engineers during maintenance program</td>
<td></td>
<td>For example, model including materials properties such as visco-elastic, thermal properties, hardness...</td>
</tr>
</tbody>
</table>
8.5 Conclusion on the improvement of the product design

In this chapter, it is demonstrated that the suggested method allows product design improvement. In addition, the risk associated in the different phases of the product life cycle, such as in the maintenance program, is highlighted. Finally, it is shown that early risk prediction is achievable with a new design.

In the previous chapter, the tests were failure-oriented so that the stress level (i.e. low lubrication level) was on purpose beyond specification. In these conditions, the lack of lubrication leads to a very rapid blade wear and eventually to a blade flip, which is accompanied with an increase in the level of friction. In the course of these experiments, it was also deduced that the intensity of the motor current is a good indicator to assess the level of friction between the blade and the drum. Therefore, a large increase in the intensity of the motor current is a precursor to the failure.

However, during the manufacturing-assembly process, some lubrication via toner is provided to the cleaning-subsystem. Therefore, further experiments were carried out to assess its impact on the studied failure mechanism. Experiments show that the additional lubrication is not sufficient to prevent increase in the friction, and the same failure mechanism occurs. Moreover, the increase in the friction level is sudden and relatively unpredictable, so that the probability of failure remains high. For this purpose, several solutions were proposed to prevent any increase in the level of friction by providing adequate lubrication at the right time. The most efficient solution relies on the addition of toner that is triggered by a continuous monitoring of the intensity of the motor current.

As in a sliding contact, the surface state of the contacting bodies might play an important role in the friction level; the change of one of the contacting bodies might strongly influence the interaction between these two bodies. Therefore, the risk associated with the maintenance program has been evaluated. The experiments reveal that the surface state of a new photoreceptor strongly influences the level of friction. Consequently, the change by a new photoreceptor entails a potential risk.

In literature, the transition in the level of friction between two contacting bodies is known as running-in phenomenon. Several transitions might occur before a steady-state friction is reached. In the configuration under study, the level of friction is very stable and low when the surface of the photoreceptor reaches a certain state. Thus, the risk of such failures (i.e. blade flip and rapid wear degradation) decreases with the number of cycles. These experiments confirm why the failures have never been reported on “old” products. On the long-term, other physical-models are driving the cleaning-subsystem life. The dominant mechanisms might be abrasive wear and fatigue wear. These mechanisms were not addressed in this research project and need to be studied in more detail.
The experiments have also been used to assess the risk of the studied failure with a new design of the photoreceptor surface. Such a surface made of PTFE has low friction property. However, it is demonstrated that the new surface does not prevent the failure of class one (i.e. a wrong application of the PMMA lubrication powder still leads to dead on arrival failure). Nevertheless, important improvements have been noticed for the failure of class two: the PTFE properties prevent any increase in the level of friction during sliding and no wear pattern has been observed on units that have been run in dry-conditions. The risk of failures with the new photoreceptor design is very low.
Chapter Nine: Conclusion and recommendations for further research

In the chapter the main research findings are summarized. Some recommendations for further research are also suggested.

9.1 Conclusion

The aim of this research is to develop a method in which the available field information is analyzed and used to prioritize and improve the design of products on the market. The method is designed for companies that manufacture “low medium capital industry and consumers” products. Such a method has been applied based on field information of a radical product currently on the market, and aims at providing design improvement for the next generation of products (derivative product).

9.1.1 The identification of the problem

In the innovative industry, four major trends are found to influence product quality and reliability: the increase in product complexity, the strong pressure on time to market, the increasing global economy, and the decreasing tolerance for quality problems. Thus, it becomes more difficult to anticipate all potential failures during the development process. Recent researches as well as this thesis, demonstrated that the present reliability and quality tools/methods are not sufficient to cover all potential reliability issues. In this context, an efficient field feedback process should be in place to react to the unanticipated deviations in product performance.

Most of the quality and reliability methods focus on improving the quality and reliability of products during the product development process. Their efficiency has been largely proven in environments where accurate and exhaustive information as well as precise customer specifications are available. Review of the literature on quality and reliability management provides few examples of models taking into consideration the field feedback information as an enabler for design improvement.

In this context, an efficient field feedback process should be in place to react to the unanticipated deviations in product performance. In particular, the field information should be detailed enough so that the heterogeneity in products (product variability) and in users (user variability) is captured. Since reliability means “failure mode avoidance”, the field information should also enable failure mechanism understanding. To do so, the reliability-oriented field feedback information should fulfill several criteria.
9.1.2 The quality of the reliability field feedback information for the improvement of the product design: a set of criteria

The literature as well as the case study made in the organization confirms that the channels to get information from the field are in place. However, in order to use the information for product design improvement the reliability field feedback information should provide a high quality of information. Such information should therefore fulfill the following criteria:

1. Content

The field databases are usually suitable for collecting information such as the proportion of failed products, the products that fail more often than the other ones, the lifetime distribution of products. For reliability analysis using a statistical approach, the failures registered in the field databases should be stored with the relevant “time scale” or “usage factor”.

Nevertheless, the information content is greatly enhanced once failed products are accessible to the design team (i.e. the analysis of failed products increases the validity of the information). Then the analysis should reach a higher detail level so that the failures can be classified according to the roller-coaster model per product. One step further, the design team should identify the different failure modes. The classification is based on the engineering knowledge of the design team.

The information should be suitable for root-cause analysis so that failures induced either by the manufacturing process, the design, the environmental conditions or the user-profile should be understood. For this purpose, the process should enable the design team to get, if requested, more information on customer environment and/or customer profile, so that information can be verified.

The failure classification and the root-cause analysis should be performed on a statically representative amount of samples to improve the validity of the analysis.

2. Time

The information related to the reliability of products on the market should be provided as quickly as needed. It should be in line with the time scale of the product development process so that design related problems are understood and, if necessary, design modifications are implemented before the design of the expected next generation of products starts.

3. Deployment

The information should be deployed properly so that the different players in the product development process are aware of the problem, in particular the design team. The loss, the disruption, or the absence of information might prevent an efficient decision-making.
4. Format

The field databases filled by the service organization (i.e. call center or service engineer) are usually used to store information on field failed products using pre-defined categories of failures or some free text to describe the failures. However, some of the reliability issues are often unanticipated so that the information required for design improvement cannot always be defined up-front. As a consequence, these field databases are likely to entail several problems with regards to information quality as those mentioned in section 5.3.3.3. Moreover, as the design team merely has access to the databases, but does not create nor feeds them, it can generally not verify the accuracy of the information included in the databases, which may lead to difficult assessment or interpretation of the information. As a consequence, these field databases can be used as a product performance indicator, but have to be supplemented by other sources of communications for design improvement purposes.

Other sources of communications should be available to balance the lack of accuracy of theses databases, e.g. telecommunications between service engineers (field) and experts of the product (design team) or at best between customers and design team. The development of “black boxes” should also be considered.

However, several difficulties are observed in the field feedback process, so that the quality of the reliability field feedback information is not always suitable for failure mechanism understanding. It prevents direct actions for product design improvement.

9.1.3 The quality of the reliability field feedback information in an innovative company

Industry provides different types of field services to their customers with one common objective: to achieve customer satisfaction. Most of the structures used to tackle complaints/problems of the customers are similar in innovative industries. In the present thesis, the structure consists in a call center as a first interface with the customer, followed by service engineers if further investigations are required.

1. Quality issues in the field feedback process

Many industries make use of call centers to provide direct support to their customers, who experience problems with a product. However, the diagnosis of failures through the call center has certain limits. Since description of the failure is mainly dependent on the customer perception and only fault tree charts are used to solve problems, only few problems can be handled by the call center. As a consequence, call centers are suitable when all failures are known and have clear symptoms that can be summarized in fault tree charts. Only in such conditions, one could expect to have a call center that does not lose information with regards to reliability. However, when unexpected failure modes occur then call centers are not geared to provide suitable support. Moreover, the service policy chosen by most companies will push the call center to provide a quick solution to customer problems, and consequently go for the solution “replace instead of repair”.

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However, such policy results in loss of information for the product design team and consequently on less knowledge on the product performance.

Service engineers are more likely to provide some useful information. However, some potential conflict of interest between the product development team and the service organization might lead to distorted information. Nevertheless, as opposed to call centers, service engineers have direct contact with the customer and the product at the same time. Consequently, they have potentially relevant information on customer environments and customer-uses. However, the primary interest of service engineer is similar to the call center; they need to fix quickly problems for the customer. So an in-depth analysis of individual failure is not their primary objective.

Nevertheless, it is strongly suggested to keep continuous contact with the service engineers because of their knowledge on customer environments. In addition, the supply chain should be organized so that the design team has access to failed products for further analysis.

2. The capability of the existing process

The existing process is able to generate information that fulfills the time, the deployment, the format criteria and partially the content criteria. Therefore, predicted and unpredicted failures are detected, and the design team is aware of the field problems. However, the root-cause analysis is not always successful.

For the root-cause analysis, two situations are generally observed:

- When known failures (i.e. failures that have been experienced in the development of the product) are detected: the root-cause is rapidly identified and the corrective-actions are usually quickly managed. As a conclusion, it could be considered that the lack of quality information is somehow counterbalanced by the sufficient product knowledge of the design team.

- When unknown failures (i.e. failures that have never been experienced in the development of the product) are detected, a rapid solution to the problem is usually not possible. The lack of quality information (i.e. the absence of relevant “time scale” or “usage factor” metric, the lack of precise information on conditions of use and environmental information) leads often to a large number of hypothetical root-causes. As a conclusion, it could be considered that the lack of quality information prevents an accurate root-cause analysis.

Since the quality of the field feedback information is not detailed enough for the improvement of the product design, a new method to bridge the gap between the available information and the needed information is required. To do so, the combination of a bottom-up approach (field information) and a top-down approach (physics of failure) is proposed.
9.1.4 A method to improve the product design using reliability field feedback information (bottom-up approach) and physics of failure (top down approach)

1. The design improvement prioritization

The failures that occur in the field should be classified according to the roller-coaster model per product. It is a system approach that allows identification of the problems common to all products (i.e. different product families) and the problems specific to one product (i.e. product from the same family). The dominant classes of failures should be tackled in priority.

2. The analysis of individual failure mechanism

For the design improvement, individual failure mechanisms/modes have to be understood. However, the analysis of all potential failure mechanisms is not manageable in a time-driven product development process. Therefore, the analysis should be prioritized on the field failed products.

The failure analysis is designed to identify: (i) the failure mode (the way the product fails), (ii) the failure location (where in the product the failure occurred), (iii) the physical evidences of the failure, (iv) the time-to-failure, (v) the potential conditions that lead to failure. On the basis of the failure analysis, a first selection of the most likely failure mechanism is achieved. This analysis is also improved with the help of physical models.

Other sources of information that might help in the understanding of the failure mechanism should also be considered. For this purpose, a comparative study between different products (either from the same family or from different families) should be carried out to highlight differences or variability between the product design, the manufacturing process, and the customer use/customer environment.

Such a comparative analysis consists in:

- The design analysis: in such a case, a crosscheck analysis with other products should be undertaken to highlight the differences between the critical parameters.

- The manufacturing analysis: in such a case, physical material should be available to verify the specifications from the product. If different manufacturing processes are used from one product to another one, the potential risk should be identified.

- The customer-use/customer environment analysis: in such a case, all information on the customer environments and the customer-uses should be analyzed to determine the impact they might have on the failure. Contact with the service engineer or directly with the customer if possible should be established.
3. The use of guided experiments to reproduce field failure

Failure mechanisms should be reproduced at the design level through experiments. For this purpose, analysis tests seem the most adequate approach since they are failure-oriented and suitable to highlight design weaknesses. The selection of parameters is based on the physics-of-failure analysis and on the above mentioned comparative studies.

4. The root-cause analysis

The experiments are run until the root-cause analysis confirms that the same failure mechanism as seen in the field is reproduced so that it is possible to predict the failure mechanism. During this step, communication with service engineer should be established to validate the findings from the experiments.

5. The improvement of the product design

As the failure conditions are known, the failure is predictable so that early risk prediction is achieved. Modifications to the design can be undertaken to avoid reoccurrence of the failure. These design modifications should be validated by adequate testing.

9.2 The generalization of the study

The case study described in this thesis shows that it is possible to determine the root-cause of field failures and resolve them using field feedback information and guided experiments. The study has been carried out in a single company specialized in the copier-printer industry that manufactured “low medium capital equipment and consumers “products. It is however expected that the findings can be generalized to others products and/or industries.

Indeed, the trends that render the prediction of product reliability more difficult are noticed in a large number of industries. As the literature did not reveal that some industries seem particularly more efficient in their ability to tackle reliability issues (i.e. use of similar product development processes and quality-reliability tools), it is expected that most of the products that are used in a complex field environment might experience unexpected field failures. Therefore, a strong feedback system is needed to learn fast and efficiently, the method developed in this thesis is designed for this purpose.

In section 3.6.3, the characteristics of the product studied in this thesis (i.e. low-medium capital industry and consumer products) have been presented: a certain cost of acquisition, a certain life cycle, these products are used by non-professional users, and these products are manufactured in a relative large volume. Products like cars and the low-end medical equipment have similar characteristics. It is therefore anticipated that the method developed in this thesis could also be applied for these kinds of products. If the quality of the field feedback information is not sufficient to prioritize the design improvement, some guidelines are provided to reach such a level in this thesis.
In the consumer electronics, the products usually have a shorter development cycle and a lower cost of acquisition. For this industry, [Petkova2003] stressed that the time to get the field reliability-oriented information is usually too long compared to the development cycle. However, this industry manifests the need to use the field feedback information for product design improvement. It can therefore be assumed that if the information can be obtained and analyzed in a timely manner the presented method can be used.

In the high capital equipment, classes III and IV are more likely to occur since class I and II are generally avoided due to the application of procedures related to design, testing, and usage. Therefore, the suggested method can be used as a baseline but will require several modifications in order to tackle efficiently these classes of failure. In particular, the experimental phase will probably require further development to meet time and cost constraints. With respect to time, the development of an adequate accelerated testing method might be promising to reproduce failure in a shorter time-span. With respect to cost, the development of failure analysis in combination with computational simulation tools is an interesting option to look after.

9.3 Recommendations for further research

9.3.1 A preventive method against the loss of relevant data

In order to prevent the loss of relevant design information and to guarantee the validity of the field information, the design team should strongly consider the option to retrieve part of the information automatically and embedded it into the product. Such information should help to classify the reliability problems. A non-exhaustive list of the items that could be automatically collected:

- Serial number/Batch number: this helps to find-out failure resulting from variability in manufacturing process,
- “Time scale” or “usage factor”: this helps to classify failures thanks to the time variable (early/early wear out/random/wear),
- The use of electrical signature analysis method: this provides diagnostic information and relevant historic on the product behavior,
- The registration of environmental data: this provides insight on the material degradation due to environmental conditions.

As the contact with the customer is not always straightforward, the recording of technical parameters that enable a better understanding on the product behavior is advised. It will improve the diagnosis made by the design team. In this domain, the aeronautical industry is the benchmark. The extensive use of data recording to enhance system reliability and safety provides rich information for analysis. However, aeronautical industry is governed by very strict safety legislation that facilitates or even binds the implementation of such devices. In the context of consumer industry, the access of such information is sometimes
perceived as customer privacy violation. Moreover, such a solution needs to be economically justified.

However, such an initiative has to be carefully tackled. Since products become more and more complex, the introduction of these devices might also contribute to an increase in the complexity of products. For example, it will imply more and more information to process that could lead to an overload of information.

Since most of industries are developing more and more devices that are connected to the network the use of such a media to gather relevant information on product could also be considered. I will also prevent the loss of information.

9.3.2 A comparative study on the field feedback process used in different industries

As it was underlined in the literature review pursued in the course of this thesis, few academic researches deal with the way field information is processed and used for the improvement of product design. It will be pertinent to carry out a comparative study between different industries (e.g. automotive, software, and so on).

For example, it is known that the software industry gathers information on field failures. Their method consists in generating log files when a failure occurred on one program. These files are used to diagnose the failure and they contain the following information: the program error information, some information on the system used to run the program, some information on the computer where the program error occurred, the list of tasks that were running on the system at the time that the program error occurred. However, there is no research that analyzes the effectiveness of such a method. As software is used in a lot of common products, the gathering of data on software failure seems a major issue.

Since a set of criteria has been elaborated to define the quality of reliability field feedback information, it will be interesting to explore their validity in other industries. Among the different criteria, it is very likely that the time and the deployment criteria can be valid for a large range of industries. However, the format and the content criteria might need to be customized according to the field of application. In such a prospective, it seems judicious to carry out a comparative study between different industries (e.g. automotive, software and so on).
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Curriculum Vitae

Clément Magniez was born in Paris, on the 20th September 1976. In 2000, he obtained a Masters degree in engineering from the Formation d’Ingénieurs de l’University Paris-Sud Orsay in France. He started his doctoral study in 2003 within the department of quality and reliability in the Faculty of Technology Management, Eindhoven University of Technology. The doctoral study has been carried out with an industrial partner specialized in the copier-printer industry. He is interested in the management of reliability in the product development process, in reliability engineering and in the modeling of mechanical systems using the finite element method.