Designing reliable products in a cost and time driven market : a conflict or a challenge

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Designing Reliable Products in a Cost and Time Driven Market:

a confict or a challenge

Intreerede

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Uitgesproken op 18 februari 2000
aan de Technische Universiteit Eindhoven

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Mijnheer de Rector Magnificus, Dames en heren,

1 Introduction: product reliability; a changing perspective

Product development cycles are currently shorter than they have ever been before. In the thirteenth century the introduction of a new product (spectacles) took forty years between first concept and worldwide use. Modern products, such as cellular phones, require currently only a fraction of this time. In 1980 McKinsey estimated that the worldwide market for cellular phones in 2000 would be around 900.000 products. In 1996 already more than 90 million cellular phones were used. And the cycles are even getting shorter at this moment. The more recent introduction of Internet and related products on the consumer market is proceeding even at a faster speed. [Beroo] And end-users expect these products to work.

This paper will address the issue of quality and reliability of high-volume consumer products. It will focus on products like televisions, monitors and CD players although the theories presented may be applicable to a far wider range of products. It addresses the following topics:

- Why is it *necessary* to predict quality and reliability for high-volume consumer products given the state of the art and recent trends in industrial product development processes
- Why is it so *difficult* to predict quality and reliability for these products, given the trends in modern development processes and the state of the art in currently available reliability analysis models and methods
- What *steps are required* to make prediction of quality and reliability a realistic option, given the constraints in the current industrial processes?

1.1 Trends in modern product development processes

Manufacturers of high volume consumer products are currently under strong pressure. This pressure is the result of a competitive market where there is a conflict between four major business drivers:

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

That time-to-market dominates product development for high-volume consumer products is at this moment commonly accepted. Stalk and Hout explained in 1991 in their article *Competing against Time* [Sta91] the importance of "time to market". Wheelwright and Clarck explained in 1992 in their article *Revolutionizing Product Development* the large impact this has on product development [Whe92].

The importance can be illustrated with a simple example. When two manufacturers operate in a competitive market with similar products but with, time wise, different development processes the following will happen. Manufacturer A, with a very aggressively timed development process, will reach the market first. Although the costs of this more aggressive development process may be higher he reaches the market at a moment when there is little competition. He can therefore sell his products at a premium price and saturate the sales channels with his products. The "time to profit[1]" for manufacturer A will therefore be quite short. Manufacturer B, with a more conservative development process, will reach the market later and will have to fight against the competition of the products of manufacturer A. He will have to sell his products at a very competitive price in order to achieve at least some level of market penetration. He may never reach "time to profit". The result is that if a product is relatively late on the market, compared with the competitors, it is hardly possible to make a profit on it. It is then too late to sell big quantities and the price erosion means that it is even difficult to make a profit on each separate sold product. The one who is first on the market can earn substantially more than those who come later.

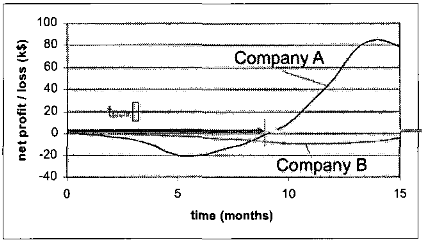

Figure 1: time to profit

The challenge, for manufacturers in high-volume consumer products, has therefore become to maximise product profitability by minimising "time to profit". Many manufacturers have translated this into bringing the maximum number of products to the market in the shortest possible time. There are some considerable risks and disadvantages to this latter strategy that will be discussed

1 Time to profit: the moment in time, counted from the start of the development of a new product, when the initial investments of putting a new product on the market are recovered

later in this paper.
For high volume consumer products this focus on time-to-market or time-to-profit has lead to a situation where, for example, a television set currently is being developed within a timeframe of roughly half a year. In contrast ten years ago a television set was developed using a development process of close to four years.
In order to achieve shorter time to market (or time to profit) several strategies can be adopted. The most commonly used strategies are:

- Shortening existing development processes
- Sticking rigidly to procedures

Although these methods are quite common they have some considerable disadvantages. In order to explain these disadvantages it will be necessary to explain a little more in detail the structure of product development process.

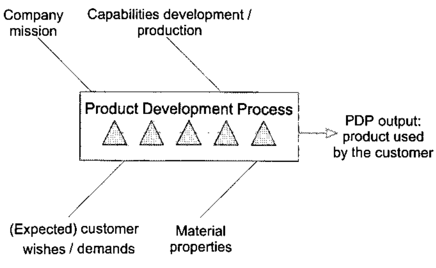

Figure 2: The product development process (PDP)

The product development process will be defined in this paper as:

Product development is a set of transformations[2] via which customer wishes are translated to an operational[3] product (or service).

Such a process cannot operate outside a company context. Therefore issues like company mission, capabilities, both of the development team as well as of the production equipment and of the material used will have to be taken into account.
The classical way to structure this process is to use the so-called functional development process. In a functional development process the different transformations (or activities) are clustered in groups with similar characteristics or functionality. These activities are operated sequentially according to well-defined procedures and guidelines. Well-known examples of such functional development processes are given, for example, by the VDI in 1973 and by Pahl and Beitz in 1984 [VDI73] [Pah84].

2 the transformations can involve both information and material

3 operational, at the customer, according to his demands and/or expectations

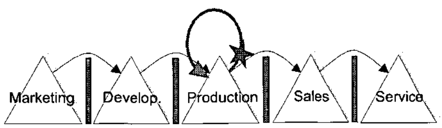

Figure 3: The functional development process

In a functional process so-called milestones separate the activities of different functionality. These milestones (or gates) are used to decide whether the process can proceed to the next phase. Although the functional development structure is currently criticised for a number of reasons that will be addressed later in this document the functional structure has also certain advantages. In a functional development process all activities that relate to a given aspect are concentrated in one phase. Due to this structure there is usually little distance, time-wise, geographical and with respect to the people involved, between a decision and the consequences of this decision. All decisions on production processes are, for example, taken in the pre-production phase. When something goes wrong during pre-production the milestone to the next phase is not passed an all efforts are concentrated on resolving the problem. Only when a problem is resolved, the milestone is passed and the process proceeds to the next phase. [Mey98] The next paragraphs will show that this way of working has several disadvantages. This way of working has, however, also certain *advantages* with respect to product quality and reliability. As all similar activities are concentrated in one phase it is quite common that people who's decision caused a problem are also involved, only a short time later, in solving the problem. Learning cycles with respect to quality and reliability will therefore be comparatively short and efficient.

1.2 Strong pressure on time to profit: necessity for concurrent engineering strategies

As mentioned in the earlier paragraphs there is considerable time pressure on the product development process. For this reason many companies are looking to methods and techniques to accelerate the process. For many companies the solution for this problem is not to reconsider the basic structure of the product development process (PDP) but to try to improve the time-performance of the existing functional structure. The following paragraphs will discuss first a number of methods used in industry to improve time to market (or time to profit) within the given, functional, structure and will then discuss techniques that use a conceptually different structure.

- *Speeding-up an existing PDP:* For many companies the solution to improve time to market is to increase the speed of their PDP without adapting the structure. Research by Minderhoud in this area has shown that this will often lead to quite good short-term result but there is a limit to the results that can be achieved this way. Pushing this concept too strong may cause an unpredictable or even an unstable process. [Min99] This is because initially people will work on improved efficiency while maintaining constant quality. Later being faster becomes a goal in itself and the improvement in speed is reached by removing or reducing (slow and tedious) safety mechanisms like product tests. This will result in an improved speed of front-end activities. Due to the decreased efficiency of down-stream activities, however, the advantage will be more than lost in the back-end PDP. The author has observed situations where over 50% of the development capacity is committed to fixing problems on products that have already passed design release.

The fact that engineers spend time and resources on rework of activities in phases that are considered already completed has a considerable impact on the efficiency of the entire process, both in time and in money. An article in Business Week demonstrated in 1990 that there is a close to exponential relation between time and effort required for design changes during the product development process. Changes performed in the late phases require far more effort than changes performed in the early phases.

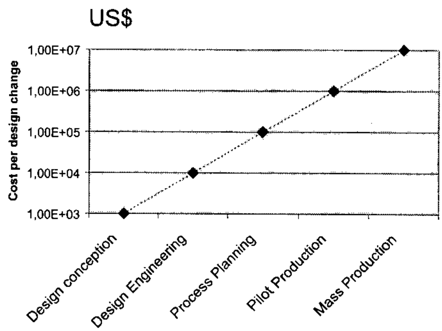

Figure 4: Efficiency of design changes as function of time in the development process [Bus90]

Companies that are aware of this efficiency relation will therefore adopt a different strategy. In order to avoid extreme forms of delay due to problems that escalate in later phases a second strategy to improve time to market is often adopted:

- *Sticking rigidly to procedures:* Especially in companies that are strongly driven by ISO9000 it is often observed that there is a tendency to prevent delay by sticking (often rigidly) to procedures. The problem with this method is that it strongly depends on the relevance and the quality of the milestones and procedures in an organisation. In case where the milestones in a business process are "perfect", no (or very little) new technology is used and the product-market combinations are known and stable this method could, theoretically, work. In the products discussed in this paper the very nature of the business involves introduction of new technology and exploring new markets. Organisations relying strongly on procedures usually try to cover new technology and new markets by introducing additional procedures. Minderhoud has observed that in these organisations, due to increased demands on products, the number of milestones has doubled in a period of about 10 years [Min99]. The number of unexpected field problems (due to new technology used / changed customer demands) has, however, not decreased significantly.

The major problem of the functional development process is that it assumes independency of the individual functions. Ample literature is, however, available that decisions in the early phases of the process can seriously affect the performance of the later phases of the process. Bralla demonstrates, for example, in his book *Design for Excellence* [Bra96] that early, or upstream, activities can dominantly influence the performance of downstream activities such as production. Decisions made in the early phases of the development process can result in products, with the same functionality, that are either very easy or almost impossible to manufacture. Another problem with the functional development process is the assumed time-independent impact of decisions. The earlier mentioned survey in "Business Week" of April 1990 [Bus90] shows however that there is a strongly non-linear relation between the moment in time when a decision is taken and the financial repercussions of such a decision. This is not only valid for design changes, slipping into a later phase but also for pro-active design changes taken in upstream phases of the development process. Independent of whether a decision involves design aspects, production aspects or aspects of customer use of a product, changes made early in the development process cost less and cause far less delay than changes made later in the process.
This has lead to a different concept of product development; the so-called Concurrent Engineering approach. In 1988 Winner introduced the following definition of Concurrent Engineering [Dic93]:

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

This method implies that, due to the greater efficiency of the decisions and iterations upstream, design changes and product optimisation, no matter whether the change involves the design, the production process or the customer use of the product, should be taken in the early phases of product development. Although the efficiency of upstream changes is far higher than of downstream changes it put strong demands on the predictive capabilities within a business process. When in the classical, functional, development process problems occurred there was no discussion on the likelihood of occurrence of a problem; the problem was just there and needed to be resolved. In a concurrent process problems need to be resolved, due to the greater efficiency, in the early phases, long before they actually happen.

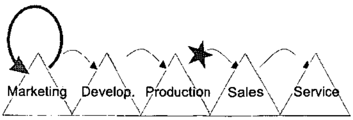

Figure 5: Concurrent engineering and predictive capabilities

Andreasen [And86] and Carter [Car92] show that this puts considerable demands on the organisation structure and the communication processes within that structure. People have to be able to make decisions on problems long before they happen during phases of the process when the specification of the product is defined in far less detail than people are used to. The author has observed numerous occasions where, for example, production people used statement like: *I cannot decide whether this will be a risk or not; come back when you have the full details of the production system and I will tell you whether it is a risk or not.* In order to attempt to make the Concurrent Engineering approach more practical, the Philips Centre for Manufacturing Technology has therefore defined five Principles of Concurrent Engineering [Min96]:

1. Focus on processes rather than on organisational units;
2. Start each activity as early as possible;
3. Continuously consider all constraints;
4. Use first-time-right methods;
5. Facilitate communication as the primary condition.

Although these Concurrent Engineering principles can contribute significantly to improvement of the efficiency of the product development process it is not obvious that this will also result in improved product quality and reliability.

1.3 Quality and reliability in concurrent engineering processes: the necessity for predictive models.

Demands on product quality and reliability put the greatest strain on the concurrent engineering process. This is a consequence of the maximum time distance between decision and validation of the decision, as reliability problems will be mainly observed at the customer, during or after the final phases of product development. In a concurrent engineering process, however, risks with respect to quality and reliability will have to be addressed very early in the development process. As in those early phases actual field information is not available, predictive models will have to be used in order to allow early estimation of reliability. Only in this way is it possible to realise the early identification and resolution of potential quality and reliability problems.

The following paragraphs will discuss currently available prediction models and will analyse whether they can be used in a modern, concurrent, development process.

2 Why is it so difficult to predict quality and reliability for high volume consumer products

As mentioned in the previous paragraphs predictive techniques form a prerequisite in modern, concurrent, development processes. This implies also for product reliability that decisions that affect product reliability will have to be taken in the early phases of product development. This paragraph addresses:

- What does product reliability currently mean from a customer perspective?
- What is the state of the art with respect to current reliability prediction models
- Are these models adequate in a modern product development process
- If not: what would be the requirements for a future generation of reliability prediction models

2.1 How to predict quality in the early phases of the PDP / State of the art in currently available reliability analysis models and methods

Prediction of reliability is nothing new. The establishment of a special interest group on reliability was as early as the late 1940's. At that time the AGREE (Advisory Group on

Reliability of Electronic Equipment) was formed by the United Sates Department of Defence. Reason for that was that, especially in military equipment, product (un-) reliability was a major cause of mission failures. One of the pioneers of product reliability, Evans, reported that in the last years of the Second World War it was not uncommon that half the electronic equipment on naval ships was down due to reliability problems. [Hen81][Eva98] The AGREE committee came to five main conclusions [Cop84]:

1 There needs to be better reliability data collected from the field
2 Better components need to be developed
3 Quantitative reliability requirements need to be established
4 Reliability needs to be verified by tests before full-scale production
5 A permanent committee needs to be established to guide the reliability discipline

These five guidelines have become, more or less, the basis of modern reliability engineering. In the years since then, the main concern with respect to reliability was the reliability of components. As demonstrated by Erles in 1961 and 1962, vacuum tubes, and especially the connectors[4] used, were major causes of equipment failures [Erl61] [Erl62].

The AGREE work caused a lot of activities with respect to reliability:

- Field feedback programs were initiated in order to gather field failure rates of components
- The resulting data was translated in a standard reliability prediction handbook; the MIL-HDBK-217 [MIL62]
- Before new equipment could be commissioned in the field a mandatory reliability study, using the above handbook, had to be made
- New components where only allowed in military equipment after rigorous tests

The model used for reliability prediction was comparatively easy; many people had observed that products showed at least three different phases with respect to reliability [Erl62] [Lew96]. The first phase, also called "infant mortality period" is characterised by an increased hazard or failure rate. This effect was attributed to products containing certain material and/or production flaws. The second, or random failure, phase is characterised by a "flat" or constant failure rate. This is described as the phase for "normal use" of products. The third phase shows an increasing failure rate

4 In this period one of the most effective methods to repair faulty equipment was to hit or kick it. Not only that it was, from a psychological point of view, a relief to the user of the product but it was also quite effective to restore poor contacts.

that is attributed to end-of-life degradation and wear-out.

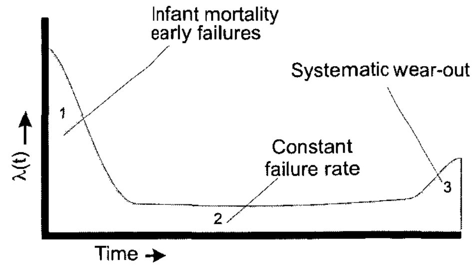

Figure 6: classical bath-tub curve

In order to deal with the first and third phase the military have used an elimination strategy. As in the second phase failure rates can be considered constant (= easily predictable) and at a low level, phase 2 became for military purposes the most relevant phase. Products in the first phase were simply not tolerated and were eliminated by rigorous test programs. Products in the third phase were eliminated by replacement of older equipment by new products.

Prediction of reliability under these boundary conditions is comparatively easy; since only phase 2 remains and this phase is governed by a constant failure rate it is possible to describe reliability behaviour of components using exponential distributions. Under the assumption that only components determine product reliability and that these components are used only in the constant failure rate period the system failure rate can be determined using:

$$\lambda_{system} = \sum_{i=1}^{n} \lambda_{component,i}$$

Perhaps due to its simplicity this is still the most common used reliability prediction model. The model has become so common that many people forget its two boundary conditions: the demand that reliability is determined by components only and that the components operate in their useful life phase only.

In order to ensure compliance with the conditions mentioned above new components, used in military equipment, are subjected to rigorous tests before they can be applied in new equipment. Due to the increasing complexity of components (compare vacuum tubes against microprocessors) and, ironically, the better reliability of electronic components the test programs have become much longer with as a consequence that at this moment military products can only apply components that are already outdated for years in commercial applications. In military industry this has lead to discussions whether technologically more sophisticated Commercially Off The Shelf (or COTS) components can be allowed in military applications. The question how this will affect future military reliability programs remains currently unanswered.

For commercial products the rigorous approach is unacceptable. In order to be able to compete on a time driven market manufacturers will have to be able to deliver, in a short time, products with the latest functionality against a very competitive price. This rises, compared to military systems, three questions:

- How to deal with new technology when rigorous test programs cannot be applied to ensure the maturity of the components used?
- How to deal with the first phase of the bathtub curve in a time-driven market?
- Are component failures at the moment the most important contributor to product reliability?

Since 1988, with the well-known paper of Kim Wong [Won88], the discussion on the validity of the MIL handbook prediction models has been ongoing.

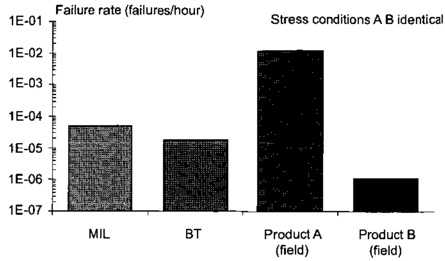

Figure 7: Observed differences between predicted and actual failure rates [Bro92]

Figure 7 shows an example of the results of a field study that was performed by the author [Bro92] where the reliability field performance of components in a high-volume consumer product was compared with the predictions using a number of prediction handbooks, such as the MIL-HDBK217 E [MIL87] and the British Telecom HRD4 [BT87]. This study showed that it was not possible to prove any relation between prediction results and field performance. The main reason was that the investigated products never reached a constant failure rate period. In the first phases the actual failure rate curve was dominated by early failures and before a constant failure rate level was reached the products where economically obsolete and replaced by newer products.

Even the developers of the mentioned Military Handbooks emphasise more and more the limited focus of the constant failure rate prediction model. This can be easily demonstrated by comparing the introduction paragraphs of two versions of the reliability prediction handbook. In 1982 the MIL-HDBK-217 D [MIL82] states that the purpose of the handbook is:

> *This handbook establishes uniform methods for predicting the reliability of military electronic equipment and systems.*

In 1995 the introduction paragraph of the same handbook states [MIL95]

> *The purpose of this handbook is to establish and maintain consistent and uniform methods for estimating the inherent reliability (i.e., the reliability of a mature design) of military electronic equipment and systems.*

The difference between the two versions of the same handbook clearly shows that in a period of about twelve years the scope of the handbook has changed from a comprehensive system reliability prediction method to a reliability estimator that can be used under certain boundary conditions. In contrast to the earlier versions the MIL 217 F notice 2 now explicitly requires a mature (= completed) design and concentrates on "estimated inherent reliability" instead of "predicted reliability". So instead of covering more, as required by current development demands, reliability prediction standards are covering less than they did in the past[5]. This leads to the following conclusions:

- Constant failure rate based reliability prediction methods can not be used in the development process of high-volume consumer products because, given the demands in a time driven product development process:
- There is insufficient time available to apply rigorous test programs during product development that will ensure mature designs, both on component and on product level
- From a competitive perspective it is impossible to test individual products until they have passed the phase of infant mortality

This is in line with the observations of Ascher and Feingold in 1984 [Asc84] when they noticed that most reliability calculations are not realistic, among other things, because they are based on constant hazard rates. This is becoming more and more relevant from a customer's perspective as for the customer especially the early phases of product life (where constant hazard rate models can not be

5 With respect to the earlier mentioned MIL-handbook: the "Willoughby 10" [Wil96] committee of the US navy recommended that the MIL-handbook, which has been the international reliability prediction standard for over 35 years, should not be updated. It states that a better method or standard should replace it when such method or standard would become available.

applied) are currently considered the most important phases. Nevertheless constant failure rate, component based, prediction methods are still the most common in industry at this moment. [Rou96] A possible explanation for this fact could be the lack of a readily available alternative that can be used with similar ease to analyse and optimise product reliability during (the early phases of) product development.

2.2 Backgrounds reliability problems in a four phase roller coaster curve

As, especially for high-volume consumer products, it is no longer possible to assume products are operating in a "constant failure rate" period a more detailed analysis of the first part of the failure rate curve will be required. Kim Wong [Won88] observed already in 1988 that the failure rate curve is not a three-phase bathtub curve but a four-phase roller coaster curve. In order to explain the four-phase roller coaster curve the author has proposed the so-called "stressor-susceptibility" concept [Bro92][Bro93]. This concept is based on the analysis of physical failure mechanisms in products. A stressor is defined as a physical stress influencing the quality and reliability of products while susceptibility of a product to a certain failure mechanism is defined as a probability function indicating the probability that the product will fail after a certain time under a given set of stressors. Although mathematically quite similar to stress-strength analysis used by Jensen [Jen95] or load-strength analysis used by Lewis [Lew96] there are some differences:

- Stressor-susceptibility analysis uses four different phases instead of three phases to describe the failure rate or hazard rate curve of products
- Stressor-susceptibility concentrates strongly on the behaviour of (weak, extreme) sub-populations within a large batch of products.

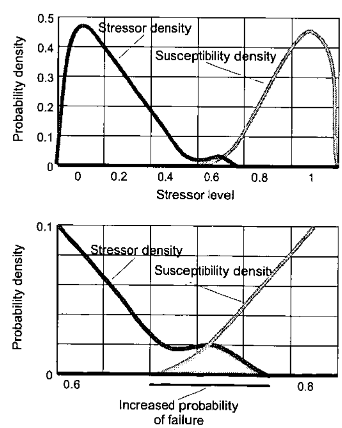

Figure 8: Stressor / susceptibility interaction

Computational the stressor-susceptibility concept is, unfortunately, far more complex than the classical parts count technique. The equation to calculate the failure probability for a single failure mechanism in a *single* product at a single time interval can be given as [Bro92][6]:

$$f_{fail,y,\psi}(\psi_0) = f_{fail,y,\psi,\Delta_n}(\psi_0)(1 - \sum_{i=0}^{n-1} f_{fail,y,\psi,\Delta_i}(\psi_i))$$

where: $$f_{fail,y,\psi}(\psi_0) = \Delta_n(s_y(\psi_0)\int_{\psi_0}^{\infty} f_y(\psi)d\psi)$$

In order to predict the actual failure rate for a large batch of products, subjected to a large number of customers for the entire operational life of a product will therefore require far more sophisticated tools than a simple spreadsheet with constant component failure rates. It is expected, therefore, that coming-up with computational efficient methods for stressor-susceptibility analysis will be one of the major challenges for the future.

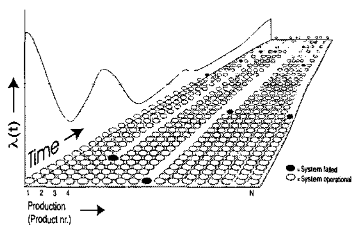

Figure 9: Stressor / susceptibility interaction in relation with the roller coaster curve

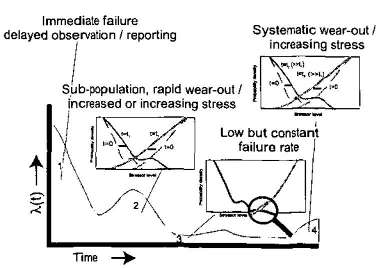

Figure 10. Four-phase Roller Coaster Failure rate

Using the stressor-susceptibility concept it is possible to explain the four-phase roller coaster curve using four different classes of defects[7].

1 ***Hidden 0-hour failures:*** Sub-populations of products already defective at t=0. The time-delay between the moment of occurrence of failure and the moment of observation / reporting of the failure determines the shape of the curve. Reasons for failures at t=0 can be products outside specification (failed products) that reach the customer or products inside the suppliers specification but unacceptable to the customer either due to an incomplete specification or a different perception of the product by the customer.

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

6 Neither the stressor-susceptibility concept, nor the related formulas, will be explained in detail in this paper; the formulas only intend to illustrate the complexity of the analysis. For a full explanation see [Bro92].

7 Defective: reported by the user/customer of the product as not working to (implicit or explicit) specifications

3 *Random failures:* Defects, induced by random events, either internally in the product or in externally from customer use or other external influences.

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

Predicting reliability according to the stressor-susceptibility concept, especially where phase 1 and 2 of the roller coaster are involved, will therefore require knowledge of the statistics of products as a function of the manufacturing process (quality) and statistics of the customer use of products. That product-manufacturing quality plays an important role in product reliability is an issue that has been implied already by many people at many conferences but where currently literature is hardly available. Determining this relation will therefore be an interesting challenge for further research. Whether extremes in customer use play an important role in product reliability determines strongly on the relation between manufacturers and users of products. In cases where the supplier has limited knowledge about the actual field use of the products the likelihood of mismatch increases. The next paragraph will address the trends in this relation.

2.3 Product reliability: the changing customer perspective

In order to predict quality and reliability in the early phases of product development it will be necessary to define what, currently, quality and reliability mean for a product. A common used [Lew96] definition of quality is:

> *The ability of a product to fulfil its intended purpose*

In a similar fashion reliability is defined as [Lew96]:

> *The ability of a product or system to fulfil its intended purpose for a certain period of time*

Both definitions are very similar[8]. For high-volume consumer products the main difficulty, however, lies in the statement *intended purpose.* For a customer this may mean something different than for a manufacturer of a system and, due to the high innovation speed mentioned earlier, it will hardly ever be possible to give a perfect specification in order to comply with *intended purpose.* In contrast with military equipment where the use of

8 This document will therefore address quality as "time independent reliability" and will treat reliability as "time dependent quality".

equipment is well-defined consumer products will have different individual customers with very different user profiles. When a product works according to its specifications but a certain customer or group of customers is very unhappy with the functionality the customer will still perceive product quality and reliability as unsatisfactory.

This problem is increased with the currently increasing functionality of products. In the past products were designed mainly as mono-functional products. People designed and purchased products according to the philosophy: one function, one product. Examples are the classical television set and the record player. Currently there are two trends in consumer products

- *More complex functionality:* In the past the (only) function of a television set was to convert aerial HF TV signals into a visible picture. Currently a TV set has the function of displaying dynamic and static[9] visual information from a large number of sources, display textual information (teletext) and even, in the near future, act as an interactive information display[10]. Also the internal complexity of products has increased considerable. Due to the progress made in, especially, integrated circuits it is currently not uncommon that a television set has the computing power of a small computer.
- *More interconnectivity:* In the past the only physical connection between consumer products was often the shared power supply. Currently it is not uncommon that TV's, PC's and audio equipment are interconnected in quite complex configurations. Customers expect from these configurations "plug and play" functionality.

For reliability of products this means that, from a manufacturers perspective, the interaction customer – product (will the customer know how to operate the available functionality / will the product be able to handle all (un)anticipated customer actions) and the interaction product – product (role of interfaces) become far more important than in the past. Although in the classical sense a wrong command sequence leading to system failure or a poorly defined interface between products is not really a reliability problem it will cause customers complaints and, in view of the previous section, lead to returned products.

9 e.g. Digital photo's
10 e.g. Web TV

For a manufacturer it then depends on how important this perceived quality for the customer is. The bottom line question from a manufacturer's viewpoint is whether quality will influence the behaviour of the customer. Especially in the last 10 years a lot has changed in this respect. The importance of product quality changed from 'nice to have' to an absolute prerequisite. The end-user expects to get good quality even for inexpensive products and manufacturers are taking this more and more into account. An example of this changed perspective can, for example, be found by comparing warranty policies over a period of ten years in the same company for the same product.

Table 1: Changes in product warrantee 1989 – 1999 [Phi89][Phi99]

	1989	1999
Warrantee period	6 month – 1 year	3 years
Failures covered	Material defects	Any customer complaints
First line support	Dealer/ service organisation	Helpdesks (free phone number)
Logistics	Via service centre	Replacement at home

While in the past warranties covered only the replacement of defective components for, say, one year, currently more and more manufacturers tend to follow a 'no questions asked' policy: in case of a complaint the product is simply exchanged for a new one, or the client gets her money back. Also the warranty is extended from a one-year period to two years or more. This extension is partly enforced by legislation, partly by the competition. Without an excellent knowledge about the quality of the products, warranty claims might be much higher than expected [Bli96].

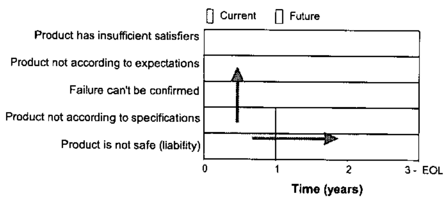

Figure 11: Trends in product reliability

From the previous paragraphs the conclusion can be drawn that reliability prediction has not become easier during the last couple of years.

- Reliability demands are, from a customer perspective, currently increasing both in time and in requirements
- For products, in a time-driven market, especially phase 1 and 2 of the roller coaster curve are relevant

- Given the importance of phase 1 and 2 and the increasing customer demands with respect to specified and expected product behaviour detailed (statistical) knowledge on (extremes in-) products and customer use is required
- The above information should be available in a manner that allows reliability optimisation in the early phases of a concurrent development process

The question is: are modern business processes able to handle these requirements. In order to answer this question the following paragraph will discuss the relation between product quality and reliability on one side and (the quality of-) modern business processes on the other side.

2.4 The relation between product reliability and the quality of business processes

In the past it took product development cycles between two and four years to develop new models for products like televisions. Currently it is not uncommon that these products are developed in a period of less than half a year. Assessments on the service process of manufacturers, active in this field, shows that, on average, it takes about seven months to obtain first field failure rate figures[11].

The consequences of these time-driven product development processes with respect to reliability are considerable. In the past the development team was able to obtain information on the reliability behaviour of the previous generation products in the early phases of the development of the successor product. Currently it is not uncommon that in the development of a next generation product only information of generations n-2 or earlier is available. The difference between these earlier generations and the current product is, also due to the reasons mentioned in earlier paragraphs, considerable. Due to the strong time-pressure in the development process there will also be less time (made) available for a detailed root-cause analysis of failures of products in the field and a subsequent translation to the current product under development. This may result that people, involved in product development, are developing products on which there is little information on actual field reliability performance available. On the other hand the more complex nature of the products may require more detailed information on the causes of problems.

11 The names of the companies cannot be disclosed here due to reasons of confidentiality but are known to the author.

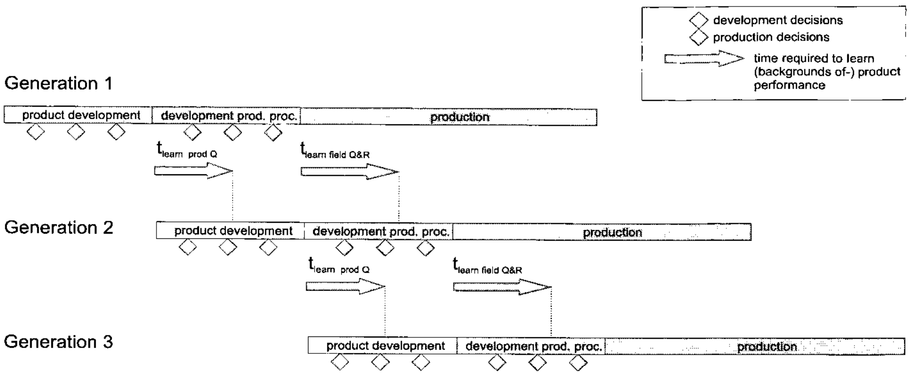

Figure 12: Time required to learn production quality and field performance in classical PDP

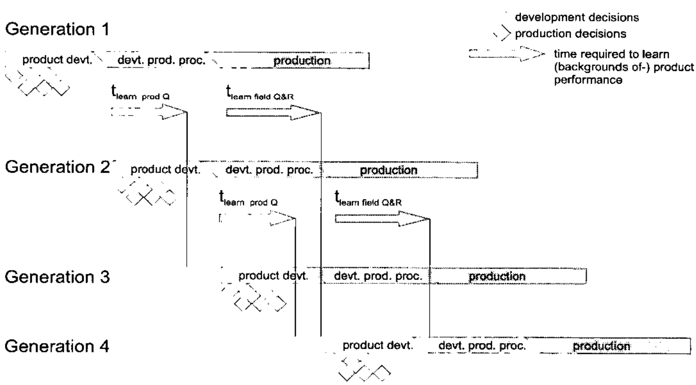

Figure 13: Impact of faster development cycles on product quality information

When the time to obtain quality and reliability information on products is, as a conservative estimate, assumed constant it can be assumed that information that was available on-time in a classical product development process will now be available too late for use in a concurrent PDP. First of all the PDP itself is shorter and second, as addressed earlier, the information is required earlier in a concurrent PDP[12].

12 A third complicating factor, slightly out of the scope of this paper, is the fact that currently field information is no longer gathered via the own service organisation but via third party service organisations.

The above situation implies that people involved in the development of consumer products have to develop faster, more complex and more reliable products with less knowledge on what is happening in the field. Without adequate provisions this can lead to a situation where, in spite of increasing demands, the actual field reliability of products is becoming more and more uncontrolled. Earlier research by the author shows a situation where major fractions of the causes of reliability problems are unknown and unanticipated. [Bro96][Bro99]

- Components reliability was predicted but using methods that do not relate in any matter to the actual failure behaviour of components in the field.
- Apparatus failures are caused by failures in product-to-product interaction. These failures were caused by mismatch between (implied) specifications of products of, especially, different manufacturers. These failures were not predicted.
- Customers using a product in an unanticipated manner determine the category "customer failures". These failures were not anticipated.
- No trouble found failures were failures that could not be confirmed in a test-situation at a service centre.

Further analysis showed that, at least in this case, it is quite unlikely that customers reported fraudulently. These failures were not predicted.

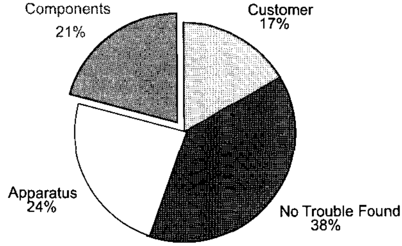

Figure 14: Observed categories of Reliability problems [Bro96]

In all cases the failures were not predicted although during the product development process a detailed reliability study was made. The prediction had focussed narrowly on the constant failure rates of components. Looking to the root-causes of the failure categories mentioned above, it turns out that the major source of reliability problems was that somewhere in the product development process relevant information was lacking. This concerned information on product-to-product interaction, on field component behaviour or on customer-product interaction in a field situation. This information was either not available at all or not available with the relevant people in the product development process. More recent research, such as presented by

Bradley in 1999 [Bra99] clearly attributed, in a detailed analysis of major industrial disasters, the majority of the problems to lack of information (or wrong information) somewhere in a business processes. Only 10% of the causes of disasters relate, according to Bradley, to classical technical reliability problems. The other problems relate to something that went wrong with information (or people handling information) relating to the technical system.

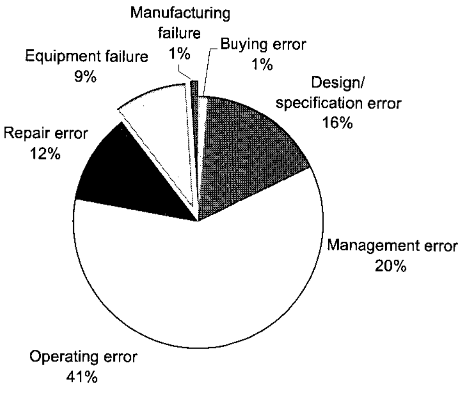

Figure 15: Reliability in relation to business processes

Since reliability apparently has to do something not only with components but also with the information in business processes it makes sense to look into the relation between product quality and the quality of information in a business processes.

2.5 Quality and reliability of products in relation with quality and reliability of information in business processes

In 1971 the research of Allen at MIT already showed the importance of information in product development. [All71][All77]. In 1995, with their paper *Product Development: Past Research, Present Findings and Future Directions,* Brown and Eisenhardt reaffirmed the importance of information, especially in modern, concurrent product development processes. One of the reasons to advocate the use of cross-functional teams is, according to this paper, *that the use of cross-functional teams increases the amount and the variety of information available and that the increased information helps the team to catch downstream problems such as manufacturing difficulties or market mismatches before they happen and are generally easier to fix.* [Brw95]

Research at Eindhoven University has learned that the information in itself is not sufficient to enable problem prevention. [Pet99] When dealing with quality and reliability problems an organisation can have a number of reasons to collect information:

- *Measuring:* the most basic level of quality and reliability information deals with logistics. When a product has a certain failure rate it means that products will fail with a certain frequency at certain customers. Even when there are no plans to improve either the current or future products a logistic infrastructure should be available to facilitate product repair. Essential information in this process is "how many repairs take place at what location".

- *Controlling.* In those cases where this number of repairs becomes unacceptable or deviates from an expected target actions will be initiated to reduce the number of failing products. In order to initiate successful product improvement actions more information will be required. How much information actually is needed depends on the intended action. When the purpose is to eliminate a single technical problem the information required can concentrate on the expected effectiveness on planned containment actions.
- *Preventing.* When actions are planned to prevent reoccurrence of problems in current or future generations of products far more detailed information is required. In this case the information should not only be sufficient to contain current problems but should provide root-causes of problems, not only in a technical sense but also with respect to improvement actions in the development process itself.

In a modern, concurrent, engineering process especially preventive information will be required. Petkova shows that many of the metrics currently in use in industry can only be used to measure product quality and reliability with a strong focus on (spare-parts) logistics. [Petoo] To illustrate this a commonly used industrial reliability metric will be explained: the warranty field call rate. . The warranty package method is used especially for logistic purposes. On the interval (t_i, t_i +Dt) $WCR_{warranty}$ is estimated by:

$$\overline{WCR}_{warranty}(t_i, t_i + \Delta t) = \frac{M_w(t_i + \Delta t) - M_w(t_i)}{\Delta t . N_w(t_i)}$$

t	: time since market introduction of the product
$M^w(t)$	: Number of failures at time t of products within warrantee
$N^w(t)$	: Number of products within warrantee on the market at time t

As the name of the model indicates, the main focus in this model is on warranty aspects of products; how many products are repaired during the warranty period. As this metric concentrates on repair the main focus is "how many products need to be repaired in what time interval". The time-window used relates therefore to the number of product on the market at a given time-interval. These products will be a mix of brand-new products and products that are close to end-of-warranty. Determining, on product level, what products have failed in phase 1 or in phase 2 or in phase 3 of the roller coaster curve is therefore very difficult. Using the information as a predictive basis for preventive actions in a concurrent engineering process will be impossible.

Another example where quality of information directly influences product quality and reliability can be found in a survey that was recently made on the quality of reliability tests in product development. [Luy00] As part of product development many manufacturers are required to perform some form of reliability testing; usually in order to be able to guarantee product specification towards customers. Usually these test are major bottlenecks in a time-driven PCP[13]. Although the survey covered only five companies the survey lead to a number of interesting conclusions:

- For all companies phase 1 and 2 of the roller coaster were, from a customer perspective, by far the most important phase.
- The conceptual knowledge of the backgrounds of phase 1 and 2 was very limited.
- The reliability tests, carried out in accordance with procedures that had been stable in some cases for decades, concentrated strongly on phase 3 and, in one case, on phase 4 of the roller coaster curve.
- In all cases, although the relevance of the tests was very limited in terms of added value to the product, these tests were the most time-consuming activity in the processes.
- Models and tools to perform tests generating information for relevant parts of the roller coaster curve (mainly phase 1 and 2) were lacking.

13 One of the companies used a development cycle of 24 weeks. The most time-consuming activities were the reliability tests mentioned in this survey which lasted more than six weeks. In practice this meant that when problems were found during the test the results were ignored in order to reach time to market.

Questions Companies		A	B	C	D	E
What phases of the four-phase roller coaster failure rate are relevant to your product		1+2	1+2	1+2	1+2	1+2
Which phases of the four-phase roller coaster failure rate do you want to test		1+2	1+2+3	1+2	1+2	1+2
Which phases of the four-phase roller coaster failure rate do you test		3	1+2	3+4	3	3
Do you have the knowledge of the statistical behaviours of	*The entire product population*	Yes	Yes	Yes	Yes	Yes
	Relevant product sub-populations	No	No	No	No	No

This illustrates again a situation were in a development process, with considerable effort, low-quality (or sometimes even irrelevant) information is generated with little added value for the development process.

2.6 New demands on reliability prediction methods for high-volume consumer products

Summarising the previous paragraphs a number of conclusions can be drawn.

- In modern, time-driven, development processes reliability needs to be addressed in the early phases (maximum flexibility and minimum delay).
- This requires strong predictive models based on accurate field information.
- Reliability can no longer be considered as a function of technical aspects only. Therefore predictive models should also address product reliability as function of the quality of (information in) the development process.
- Field (and production) data should therefore be transformed, in a very short period of time, into information on both technical and process risks that can guide decisions in early product development.
- For high-volume consumer products reliability prediction methods need to be able to cover the entire roller-coaster curve,

especially phase 1 and phase 2.

- Prediction of phase 1 and 2 requires detailed statistical knowledge of both extremes in products (quality) and extremes in customer behaviour.
- Reliability prediction methods will need to be able to address expressed and implied specifications such as perceived by the user of the product.

Looking back to the problems the AGREE committee faced in the late forties it can be said that in some areas quite a lot of success has been achieved but that in other areas the success has been limited up to now. When considering reliability in the context of a modern time-driven product development process a number of issues has been resolved but a number of new issues has appeared. Especially these new issues will have to be resolved in the future.

	AGREE recommendation	*Situation 1999 for high-volume consumer products*
1.	There needs to be better reliability data collected from the field	Still valid, especially with respect to phase 1 and 2 of the roller coaster curve. Due to pressure on "time to market" feed back loops should be very short and generate high-level information.
2.	Better components need to be developed	Succeeded! Currently components form only a minority of the field failures
3.	Quantitative reliability requirements need to be established	Still valid; especially requirements that can be handled in the early phases of product development. Difficult for phase 1 and 2 of the roller coaster curve.
4.	Reliability needs to be verified by tests before full-scale production	Very difficult to match with "time to market" requirements. When tests are applied they need to fit in concurrent engineering PDP.
5.	A permanent committee needs to be established to guide the reliability discipline	Major problem: how to deal with reliability as a function of (quality of-) business processes.

The next paragraphs will address some of these new challenges. As mentioned earlier: in many of these challenges quality and reliability information plays a very important role. Both the quality of the information and the time that is required to obtain the information and deploy it in a product development process. Therefore the following paragraphs will concentrate on information and will address how the quality of reliability information can be used as a metric to analyse the maturity of product development processes. In order to illustrate the importance of the role of people in this information handling process the next paragraph will describe the requirements for a future quality and reliability engineer and will show that these requirements differ considerably from classical quality and reliability engineering disciplines.

2.7 Requirements for future quality and reliability engineers

The requirements, mentioned above, will have a serious impact on the profession of quality and reliability engineering. When, in the past, reliability engineering mainly concentrated on the statistics of component failures reliability engineers had either background in statistics or background in component- or device physics. Still nowadays a considerable amount of people are active in these areas and, looking to the progress made in component reliability, with a high degree of success. The new demands, however, will require a new class of quality engineers. Requirements for these future specialists are:

- Reliability engineers should have knowledge of the design and control of modern business processes, especially product development but also manufacturing.
- They should have technical product knowledge to an extent where they can distinguish extreme products from ideal products. They should know the difference between material / production parameters and product performance parameters as perceived from customer perspective
- They should have the ability to analyse product – customer interaction (ideal and extreme cases) in relation to modern product development processes

The problem is that for many classical, functional, engineering disciplines these requirements conflict with the mainly mono-disciplinary engineering education. It will be a challenge for education programs with a more cross-functional tradition, such as Industrial Engineering and Management Science to set up programs that are able to raise the future generation quality engineers. With current programs such as operations management, innovation management, logistics and production control these programs contain for a major part the ingredients that are required. In order to meet with the above requirements a number of aspects will require special attention:

- The link with classical technical engineering disciplines, in order to develop the required product knowledge
- The link with statistics, in order to develop capabilities to transform field and production data into information on (extreme) products and customers
- The link with psychology, in order to understand the processes and mechanisms that take place in the steps between (failing) product and reported field failure.

As these requirements differ considerably from currently defined engineering disciplines it could be useful to set-up training and education programmes for "professional quality engineers". The main task for this new group of engineers would not be to perform statistics on failing products but to transform information on failing products in the field or in production to development information ready for use in the early phases of future product development.

3 Steps required to predict product quality and reliability in time driven product development

No organisation, especially not in an innovative, time-driven market, can guarantee that reliability problems will never occur. However, these problems can be minimised by giving explicit attention to failure prevention when and where possible. As failures will occur anyway, failure detection and analysis is just as important. Organisations that strive for a competitive position in quality and reliability should organise their capability to handle quality and reliability information in an efficient and effective manner. As mentioned in the previous paragraphs there is no concept readily available that can be used to meet with these demands. Therefore research will be required on the analysis, the control, and later in the design of time-driven development processes in order to define new concepts for quality and reliability prediction. This research will have to consist of two lines:

- *Empirical field research:* analysis on the structure of current time-driven development processes and the background of current quality and reliability problems

- *Theoretical model development:* based upon the results mentioned above new predictive models will have to be developed that can be used, especially, in time-driven development processes.

Over the last couple of years the author has been working, together with colleagues in the research program of the research school BETA [BET97] on the first steps to meet with the challenges described earlier. In the next section the first steps of a theoretical framework are described that can be used to:

1. Analyse the process of data collection
2. Analyse the deployment of information in a business process
3. Determine and prioritise the improvement points, both in products and in business processes

3.1 First step: analysing product reliability as function of quality of business processes

With the trends in business processes as described in the previous paragraphs it is becoming more and more difficult to predict the quality and reliability of a technical product. Before even data is available that can be used as a basis to develop reliability models both the technical product and the customer behaviour have already moved one or two generations ahead. An alternative approach therefore could be not to look at the product only but also to the learning capability of a company on aspects of quality and reliability. [Bro99]

Essential aspects of this "quality of reliability information" are:

- The level of detail the information provides
- The deployment of the information to the relevant people in an organisation
- The time it requires to obtain and deploy this information

3.2 Level of detail of information

In the area of high volume consumer products it is, currently, not feasible to develop, produce and use large series of products without ever seeing a product fail. In well balancing priorities in a product development process it is important to know what events can become real quality and reliability problems and what events are highly unlikely ever to happen. Therefore the first requirement on quality and reliability data is that it should provide sufficient information to prioritise further actions.

The second requirement on quality and reliability data is that there should be sufficient information to identify the relevant actors in a business process. When priorities are clear but it is unclear who can act in order to resolve a problem it will be quite difficult to define subsequent actions.

The third requirement on quality and reliability data is that it should be possible to identify a root-cause of a problem. Often problems are characterised in reliability databases by describing phenomena like "product dead", "no power signal" or "software problem". These descriptions give insight in the effect of a problem but not very much into the cause of a problem. With the classical, component based, reliability models [BT87][MIL87] the root-cause was usually quite simple: either the component had a random failure or was overstressed. As overstress was attributed to "out-of-spec" application of a product or component [MIL87] this was not counted as a real reliability problem, which left only one cause: random failures.

As shown earlier these component failures form only a minority; most reliability related failures are in other categories with as the most important category "Trouble not found". In order to reduce this category far more detailed information on root-causes will be required.

3.3 Deployment of information in an organisation

Prevention of future reliability problems requires not only that causes of failures are known in an organisation but also that the information is deployed to the right people. It is not uncommon that information on quite persistent reliability problems is restricted to service organisations only. The service organisation is familiar to the problem, knows how to solve it and, also due to local cost and time pressure, sees no reason to inform other parts of the organisation. The author has observed that failures that happen in approximately 1-2% of the total product population can be persistent for at least six product generations of products. This leads to the requirement that reliability information should not only have sufficient level of detail but also have deployment to the relevant *actors*. In this context actors are defined as persons in an organisation with the ability to influence the reliability of the current or future generation products. Using the concept of actors it will be necessary to distinguish between corrective actors (people with the ability to correct reliability problems in existing products) and pro-active actors (people with the ability to influence and/or prevent reliability problems in future generations of products).

The author has observed that in many cases reliability related information is mainly deployed to corrective actors. In many organisations the pro-active actors are not identified as such and therefore little reliability related information is deployed to them.

3.4 Time required to obtain and deploy information

In the current time-driven product development processes not only information content and deployment is relevant but also the timing of the information gathering and deployment process. As mentioned in the previous paragraphs product development processes are under a strong time pressure. This has resulted in development models like concurrent engineering. [Min99] Although many people think of concurrent engineering as a concept where development activities are performed in parallel, this increased efficiency can only be reached when three requirements are fulfilled:

- Risks and potential problems are identified and resolved as much as possible in the early phases of the development process
- The actual capabilities of products, in terms of functionality, quality and reliability, are validated as soon as possible in the development process.
- Where a mismatch between prediction and actual capability exists this mismatch is investigated on root-cause level and this information is deployed to the relevant actors.

The author has analysed a number of development processes in companies in Europe, Asia-Pacific and North America[14] and has found that it is not uncommon that companies require more than six months to obtain the first information on actual product quality and reliability. This implies that, with a development cycle of 28 weeks, information will at least pass over one product generation. Other companies are able to obtain the same information for the same category of products in less than six weeks due to far more aggressive data feedback, analysis and deployment methods. It is obvious that company has a considerable advantage over the first company.

3.5 Understanding information flows in product development processes

Most companies measure the success of a new product on the four business drivers mentioned in 1.1: function, profitability, time

14 The names of the companies cannot be disclosed here due to reasons of confidentiality but are known to the author.

and quality. The problem with all these business drivers is that they can be measured accurately only after the product development process has been completed. From the previous paragraphs, however, the conclusion can be drawn that a modern product development process requires pre-control; identifying problems and risks before they happen.

In an ideal situation it could, theoretically, be possible that a model exists that describes the relation between all (technical and process) control factors and their relation with the output on all the four business drivers. This would reduce creating an optimal product development processes to an optimisation problem, early in the PDP.

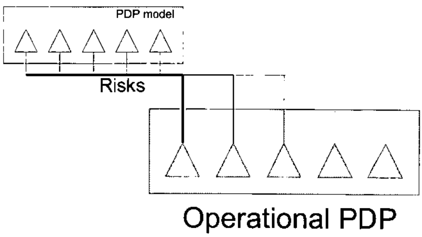

Figure 16: Hypothetical "ideal" product development process

In practice there are a number of reasons why such a model cannot be realised in the near future:

- *Lack of stability of current business processes.* As mentioned in the previous sections the world of product development is highly dynamic. The speed of change in both technology and customer behaviour is such that a PDP model is probably outdated before it is completed.
- *Complexity of human decision processes.* Although many companies try to reduce the unpredictability of product development processes by using fixed procedures and working methods the process of product development remains a process dominantly influenced by human decisions. Making a fully predictable PDP (model) would require the ability to predict human behaviour. The number of external factors, such as culture or politics, influencing human behaviour is so large and so complex that it does not make sense to translate this into a technical prediction model

The fact that it is currently impossible to develop a deterministic predictive PDP model does not imply that the "behaviour" of a product development process cannot be analysed. In control theory it is common to analyse black-box systems by the impulse response; the response of the system on a certain deviation on one of it's inputs. In parallel this paper will define the "behaviour" of a product development process using terms, derived from control theory. Using concepts from control theory it is possible to describe a development process as a set of interrelated activities. Each of these activities forms a transformation of information and/or material. Every transformation uses one or more inputs to generate a certain output. In an actual business process the nature of this output will usually be some form of product or information. The output of one activity can be used as input for a next activity. In this way it is possible to form a chain or network of interrelated activities, starting with first product specifications and ending with the observed field quality of the actual product.

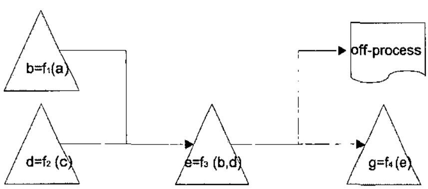

Figure 17: Product quality as a function of business processes

Examples of such transformations can be

- Design activities, where product demands are transformed into a technical product specifications
- Engineering activities, where product specifications are transformed into a specification for the production process

In order to describe and understand the complexity product quality as function of the underlying business process the following terms will be introduced.

- *Activity:* smallest element in a PDP; usually a transformation of either information and/or material
- *Activity Impulse response:* the response of an activity on a deviation on one[15] of it's inputs
- *Operational Process:* all activities in a given business process
- *Actor:* a person, able to influence the outcome of an activity (activity actor) or process (process actor)
- *Process output:* essential deliverable of a business process
- *Process input:* information, originating outside the business process, required as input for one or more activities
- *Process cycle time:* the time required to transform process input to process output
- *Process Impulse response:* the response of a process on an internal or external deviation
- *Off-process activity:* activities that do not relate in any form to any process output.
- *Essential process:* the sub-set of all activities in an operational process that are not off-process

15 An activity can have multiple impulse responses

- *Information flow:* network of interrelated activities described by the input-output relations between activities, resulting in a process output
- *Information loop or learning cycle:* Closed loop information flow; process output is used as one of the process inputs in the same process in a next process cycle.

The resulting models show a strong resemblance to models from classical control theory. Although it might therefore be tempting to use similar concepts to develop a deterministic control model of the entire PDP the earlier paragraphs have stated that, due to the complexity of human decisions involved in this process, such a model is not likely to be developed in the near future. Therefore this paper concentrates on the use of process response models for product development processes.

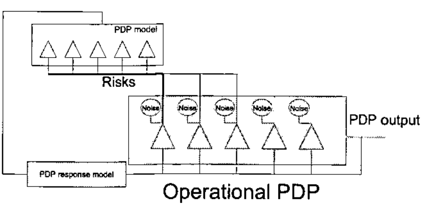

Figure 18: Analysing product development processes via response models

3.6 The MIR concept: Maturity Index on reliability

In order to determine how a business process reacts on unexpected events (process impulse response) it will be necessary to analyse the process that takes place when an unexpected event takes place.

- First step in analysing process impulse response is measuring. If the process output strongly deviates but it is not measured it is unlikely that any corrective action will take place.
- The second step of impulse response is communication; in order for a process to react certain, relevant, activities in the information flow leading to the process output will have to be adapted. This requires at least that the corresponding actors (activity level) are informed.
- The third step of the response is analysis and control; only when root-causes of deviations are known corrective actions can be implemented

In an unintelligent system the response will stop at this level. Systems operated by humans, however, have the ability to learn. Therefore it is possible that people not only control the effects of unexpected events but also adapt the process to ensure prevention of similar problems in the future. Therefore:

- The fourth step of response is defined as adaptation; adapting parts of the process or process structure to prevent problems from repeating themselves.

In a technical control system these steps, especially step 1 to 3, take place and are determined by the system structure. In a business process, like product development, these steps strongly rely on communication between human beings and are, therefore, by no means trivial. It can be that relevant process output is not measured or not communicated to relevant actors. It can also be the case that relevant actors are informed but lack the capability to find root causes or to determine corrective actions. Therefore it makes sense to look in detail in how and to what extend an organisation responds on deviations.
These four steps form therefore the basis for a concept called Maturity Index on Reliability[16] (MIR). It analyses the process impulse response of a business process by looking at the activity impulse responses and the propagation of the relating information through a business process. It defines the level of response (or the quality of the response) on a five-step scale (zero to four) where steps one through four relate to the four levels of impulse response mentioned above. The term Reliability in MIR is used because the original MIR concept concentrated especially on the impulse response of a business process on reliability problems.
The MIR model assumes that a company is only able to take action if the relevant information on process output is available. For product reliability this requires in particular information from the field. In order to control (dominant) failure mechanisms it is required that at least the origin of problems (activities + actors) is known. Problems that find their origin in using the wrong material may lead to different failure mechanisms than problems that have their origin in production. To be able to prevent the occurrence of a problem in future, first, it must be known exactly what caused the problem, and second, a solution must be found. This results in the following five levels of capability to analyse and control problems.

Level 0. The manufacturer has no relevant quantitative evidence of the process output[17] (e.g. field behaviour) of the products. Consequently, there are no

16 The MIR concept has been jointly developed by Eindhoven University of Technology and Philips CFT, development support.

17 Process output can be measured on all business drivers on profitability, quality, time and function. This paper concentrates, as an example, especially on quality related issues.

control loops from service back to Production and Development. (Example: the number of service calls of a product is known but not in relation to the time of repair, the age of the product and the number of products sold.)

Level 1. The manufacturer has quantitative evidence of the process output of the products and the information is fed-back into the process, but the origin of the problems / deviations is unknown.

Level 2. The manufacturer has quantitative evidence of the process output, knows the origin of the problems (such as design, production, material or customer use), has the corresponding control loops, but does not know what actually causes the problems.

Level 3. The manufacturer has quantitative evidence of the field behaviour, knows the origin of the problems and knows what actually causes them, and has the corresponding control loops and is able to solve problems. The manufacturer is, however, not able to prevent similar events from happening in the future again.

Level 4. The manufacturer has quantitative evidence of the field behaviour, knows the origin of the problems, and knows what actually causes them and what to do about it. The level of knowledge is such that the manufacturer not only knows root causes of problems (technical and organisational) but also is able to anticipate and prevent similar problems in the future. All corresponding control loops are active.

These five levels will be called the Maturity Index on Reliability, in short MIR. The MIR principle is visualised in figure 19.

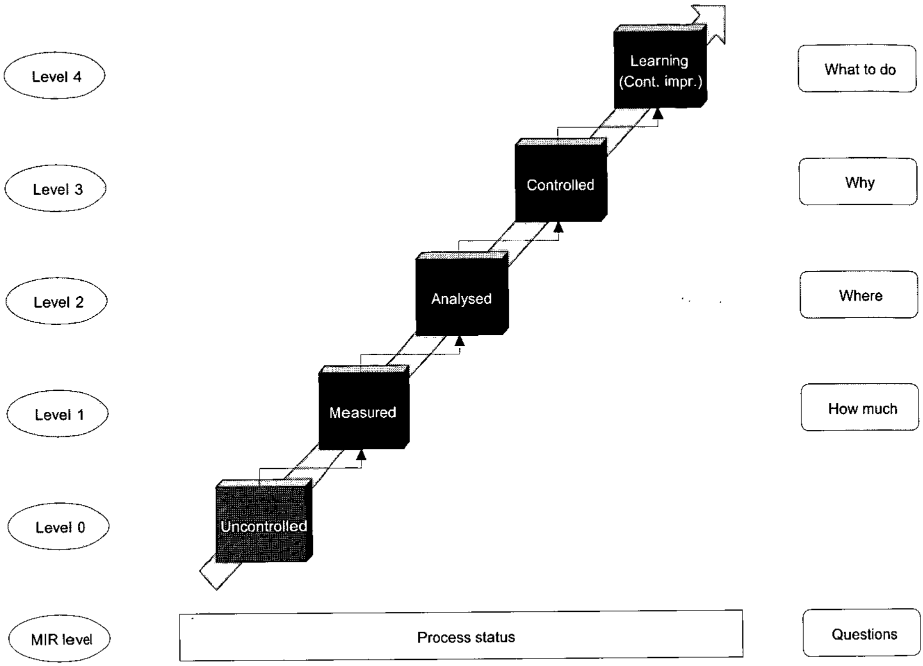

Figure 19: The MIR model.

3.7 Practical experiences with the MIR model

In the past five years the MIR concept has been applied to analyse information flows in development processes with a high degree of success in many companies in the area of consumer products and professional products. When companies design a new product there are three classes of technology used:

- Existing technology from the own company
- Existing technology, used from other companies
- New technology

One would expect that companies, scoring low on the MIR scale would be conservative in applying new technology and companies scoring high on the MIR scale would be able to handle a considerably larger amount of new technology in new products. The results of actual MIR assessments, however, showed the reverse. Companies scoring low (MIR1 and below) use a considerable amount of new technology when developing new products. The risks when applying this new technology are, due to lack of predictive capabilities, usually underestimated in the early phases of product development and lead to considerable delay due to quality and reliability problems discovered in the later phases of product development. Companies scoring high on the MIR scale (MIRfj3) apply new technology only where a potential cost, function or quality benefit makes it really necessary. The larger predictive capabilities result in far earlier identification and resolution of these risks (see Figure 20).

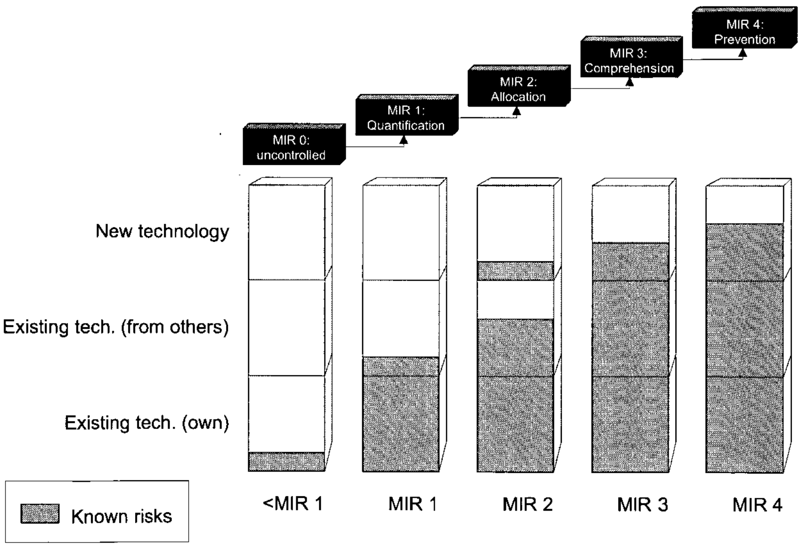

Figure 20: The MIR model and product innovation

Practical example MIR model[18]

The following paragraph will show the MIR model applied to a practical situation. An assessment of a company on the MIR scale uses the following steps.

- Mapping all activities in a company with relation to process output in a so-called activity model (see figure 21)
- Using interviews the communication between activities is mapped and cross-checked; off-process activities are removed and the resulting information flows and information loops are identified (see figure 22)
- In the resulting information flows the MIR level is established via analysis of the documentation of actual events (impulse response) in actual projects.
- The major bottlenecks determining the current MIR level are identified as priorities for improvement.

Figure 21 shows an activity model for a typical time-driven product development process. The company knows it has a large number of quality problems. The quality problems relate both to the quality of the end-product and to the back-end of the PDP. The latter problems are causing considerable delay of time to market and require a considerable amount of resources. The company has tried to resolve the problems by introducing quality tools such as FMEA and QFD.

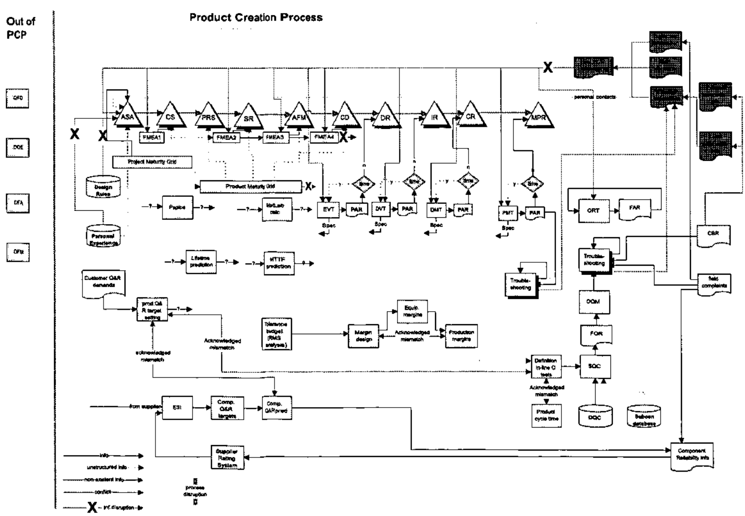

Figure 21: MIR information flow model, activities in the product development process

The activity diagram, presented in figure 21, gives an indication of the use and deployment of the various (quality related) activities in the Product Development Process. It does not, however, give an indication of the "quality" of the information and the relation to information flows and information loops in the PDP. Therefore figure 22 shows the same Reliability Information Flow focussing on the tools that are currently deployed as part of an Essential Process in the PDP. A tool is considered part of an essential process if the results are actively used in the process and there is a certain degree of verification/validation of the resulting information later, inside or outside the process. The quality level of this validation finally defines the MIR level of the information loop. The mentioned tools QFD and FMEA form, in this company, not part of an essential process. The lack of valid input to these activities results in a very large number of poorly defined priorities. (Example: FMEA with over 100 priorities in a single product)

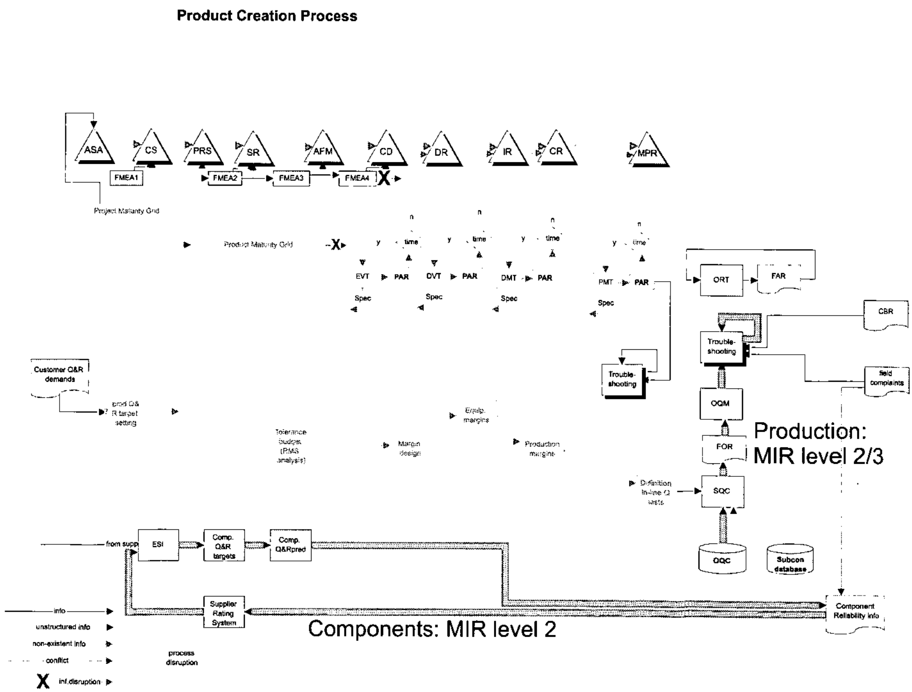

Figure 22: MIR information flow model, quality of information in information loops [Luy99]

As observed earlier in many cases there is only a partial deployment of information in this Product Development Process. Activities in figure 21 that are off-process in the PDP are excluded in figure 22. Activities that are integrated in the PDP but that are not part of an essential process are included but have no MIR level assigned. Only activities that are part of an active information loop (learning cycle) are presented with the corresponding MIR level.

In this company two information loops could be identified on MIR level 2:

- *Component management:* Information on which components fail and the follow-up actions from suppliers. Failures are allocated (MIR level 2) but the root-cause of failures on technical and organisational aspects is analysed only to a limited extend.
- *Production Quality Management:* Failures in the production line are analysed and improvement actions are implemented. Root-causes are investigated in technical sense but only to a limited extend in organisational sense. Especially translation to the earlier phases of the PDP is based on personal and informal contacts.

Although both sub-processes have MIR level 2 the deployment of information to the main PDP is only very limited. The PDP itself is does not reach MIR level 1. Although a lot of quality and reliability related activities are present in the current PDP, the deployment and validation/ verification of information is only limited.

Interesting in this case is the role of the service organisation. In this case the servicing of failed products and the gathering of repair information is performed by a third-party company. The main performance indicator for this external organisation is "cost per repair". During the analysis it became clear that, without structurally redefining the role of the service organisation, other than logistic information (nr. of repairs, nr. of components used in the repair process) no relevant information could be expected from this part of the process.

4 Challenges for research on quality and reliability in time-driven product development

Using the MIR concept it is now possible to analyse the structure and quality of information flows with respect to product quality and reliability. Over fifteen MIR assessments in a period of five years have learnt that, although many companies claim to have modern, concurrent, development processes most processes lack the capability to effectively manage quality and reliability in the early phases of product development. In this respect the MIR concept has demonstrated the value of analysing the relation between product quality and reliability on one side and the structure and quality of information flows on the other side. There are, however, still many aspects that require further analysis. Therefore the author sees the following research challenges:

- Understanding the structure of product development processes and the role of information in these processes
- Predicting product reliability, early in the development process, based upon better knowledge (statistical aspects of-) of products and the underlying development processes
- Anticipating the role of product quality and reliability in future development processes

The following paragraphs will address these aspects in detail and will propose a number of corresponding research activities.

4.1 Understanding the structure of product development processes and the role of information in these processes

The MIR model bases itself mainly on research in high-volume consumer products with a strong pressure on time-to-market. First attempts have also been made to apply it in other areas such as in process industry. There is, however, no reason why it cannot be applied in other areas such as professional products or in development of services. Healthcare is, for example, a process where the relation between quality of service and quality of the information flow appears to be quite important. Further analysis in these areas will be interesting. But also in high-volume consumer products there are still a number of open issues.

- *Understanding the structure of product development processes:* Modelling techniques, such as currently in use in supply chain management, could provide a basis for better understanding patterns in modern product development processes, especially where boundaries between organisations are involved.

- *The role of Information Technology:* Thanks to product data management the information gathered in a modern development process can be far easier utilised in learning structures, both in current and in future development processes. Systematic analysis [Bem91] or even data mining of product development information with respect to quality and reliability is still quite new and can provide new opportunities with respect to product reliability.
- *Timing of information:* As concurrent information processes are strongly time-driven it will be important not only to determine how fast current quality and reliability information is deployed but also how fast it can be deployed in the future. The speed of communication has increased considerably with the use of modern communication structures such as the Internet. The use of these structures to deploy quality and reliability information has so far been limited.

4.2 Predicting product reliability, early in the development process, based upon better knowledge (statistical aspects of-) of products and the underlying development processes

Another issue where considerable research will be required in the coming years is the changing customer perspective of quality and reliability. In this respect especially phase 1 and phase 2 of the roller-coaster curve require further analysis. Therefore the following aspects will require further research:

- *Predicting the behaviour of extreme products:* How to get adequate information on realistic extreme products, still deserves further analysis. In this respect especially two items are of interest: what is the likelihood of occurrence of different extreme products and what is the likelihood of failure of these products. For phase 1 especially the relation with modern research on SPC and quality testing seems promising.
- *Predicting the behaviour of extreme customers:* With respect to extremes in customer use also further research will be required. Here existing psychological techniques from safety analysis, such as precursor analysis, are quite promising.

- *Development of more efficient algorithms:* Although stressor-susceptibility analysis provides a concept to mathematically explain the occurrence of phase 1 and phase 2 the current algorithms used are far from efficient; further research in this area will be necessary.
- *Development of efficient test strategies:* Currently most reliability tests concentrate on phase 3 and 4 of the roller coaster curve. In high-volume consumer products it may be more important to predict phase 1 and 2. The challenge, in this respect, will be to develop fast and efficient test strategies that can be applied early in the development process. This will require detailed knowledge, both on the mentioned extreme products and extreme customers. The mentioned algorithms may be helpful to realise a minimal number of products to derive maximal information.

4.3 Anticipating the role of product quality and reliability in future development processes

Product development processes have been far from stable over the last decades. As illustrated in this paper the change from the classical, functional development process to the modern time-driven concurrent engineering processes has had a considerable impact on product quality and reliability and their role in product development. Even at this moment product development processes are far from stable. Current trends, such as sub-contracting in product development and the use of Internet during product development will most likely have also considerable impact on product quality. People such as Van Eijnatten, are currently experimenting with new work structures that will enable even faster more creative product development [Eij99]. It is most likely that these "chaordic" development processes will require considerable research to ensure quality and reliability for the end-user of the products. With the end-users of products I started this paper and with the end-user of products I would like to end. Because new technology, no matter at what speed and against what price it is brought to the market will fail to attract customers when a significant number of products will results in unsatisfied or complaining customers.
The motto of a well-known Dutch company, active in the field of high-volume consumer products is "Lets make things better". I hope that with this overview I have given you an idea of the amount of research that will be necessary to make this come true.

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Curriculum vitae

Prof.Dr.Ir. A.C. Brombacher was born in Rotterdam, the Netherlands on September 20th, 1961.

He obtained a BSc, MSc (cum laude) in Electrical Engineering and a PhD in engineering science at Twente University of Technology. Aarnout Brombacher has experience in industrial quality and reliability improvement projects and the development of quality and reliability analysis methods and tools. He has authored and co-authored over forty papers on these subjects and has written a book with the title "Reliability by Design". Aarnout Brombacher is head of the sector "Product and Process Quality" and professor in "Quality and Reliability Management" in the faculty Technology Management of Eindhoven University of Technology. He is also professor in "Reliability of Mechanical Equipment" in the faculty Mechanical Engineering in the same university.

With these chairs he is responsible for research and education in the fields

a) Quality and Reliability of (high-volume) consumer products and

b) Reliability and Safety in process industry.

He is also, as senior consultant, connected to Philips CFT Development Support - Reliability section. Main task of this department is research on, as well as application of new methods and techniques for quality and reliability management, quality and reliability engineering, reliability automation and robust design, especially for the early phases of the development process.

Finally professor Brombacher is attached to the National University of Singapore as visiting professor in the context of a cooperation program between Eindhoven University of Technology and the National University of Singapore.

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ISBN 90 386 1481 0