Will it really work? : some critical notes on current industrial development processes

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WILL IT REALLY WORK? Some critical notes on current industrial development processes

INTREEREDE

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INTREEREDE

Rede, in verkorte vorm uitgesproken bij de aanvaarding van het ambt van hoogleraar in de "bedrijfszekerheid van mechanische systemen" aan de faculteit werktuigbouwkunde van de Technische Universiteit Eindhoven op 11 maart 1994.

Prof.dr.ir. A.C. Brombacher

Inauguration speach, in shortened form delivered on the occasion of the inauguration to professor in "Reliability Engineering of Mechanical Equipment" in the faculty of Mechanical Engineering at Eindhoven University of Technology on March 11th, 1994.

Highly learned rector,
Ladies and gentlemen,

Reliability is a branch of science with a relative short history. The first large group of publications discussing fundamental backgrounds of reliability in a scientific way is dated shortly after the second world war. This does not imply that before that time no reliable products were being developed. On the contrary. Europe has, as explained by Stevens [STE93] for example, a long tradition of so-called guilds. A guild united people of a certain branch of "industry". The guild had responsibility for the education of new experts or "*masters*" as they were called and the guild was responsible for the level of craftsmanship that was required to become a *"master"*.

1 Historical overview of design processes

1.1 Traditional comprehensive development processes: the guild structure

The development and realisation of new products in the traditional guild system was quite different from the current industrial systems. Basically, the *"masters"* worked in small workshops and had responsibility for the total product life cycle; from the acquisition of new assignments to the delivery of the final product to the customer. Even after the delivery of the product, the *"master"* retained a certain form of responsibility. The reputation of the *"master"* was dependent on, beside the obvious cost aspects, the durability of the products, most *"masters"* took great care to produce products with high standards of quality and reliability. A well known Dutch brewery for many years used an advertising campaign based on the quality standards of the old guild-system. (Vakmanschap is meesterschap) For many years this campaign was considered to be the most successful advertising campaign in the Netherlands due to the easy and obvious recognition by the general audience.

Achieving these high standards was organisationally not too difficult due to the total control of the *"master"* over the entire product realisation process; the *"master"* controlled the purchasing of new material, the development of the product, the production process itself and the adaptation of the product

towards customer requirements.
See figure 1.

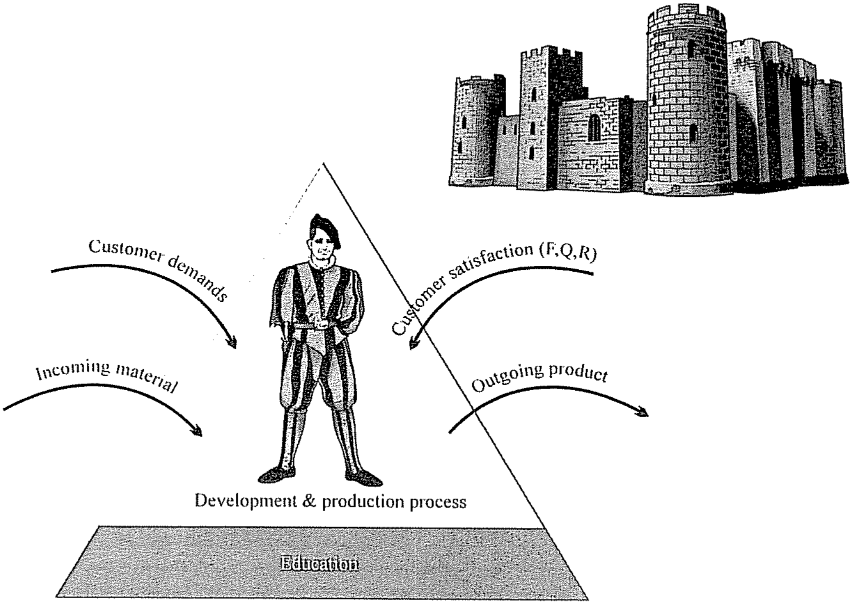

Figure 1: Development and production in the guild-system

This way of working did not imply that everybody within a guild did the same job. In the larger "companies" of those days there was a strong hierarchy as well as a strong horizontal differentiation.

The guilds consisted, basically, of three layers. People leaving home or schools as a child started working in a guild as student or pupil. Generally speaking, the first jobs required very little skills while the more advanced pupils worked on jobs required a higher degree of specialisation. Such a group of pupils worked under the supervision of a so-called "*assistant*". At the moment a pupil was able to master a certain amount of different skills, he could apply for a test to become an assistant himself.

The assistant was responsible for a certain task on which he worked with the help of a number of pupils. After a certain period of time and after mastering a number of additional skills the *"assistant"* could apply to become accepted by the guild as a *"master"*.
See figure 2.

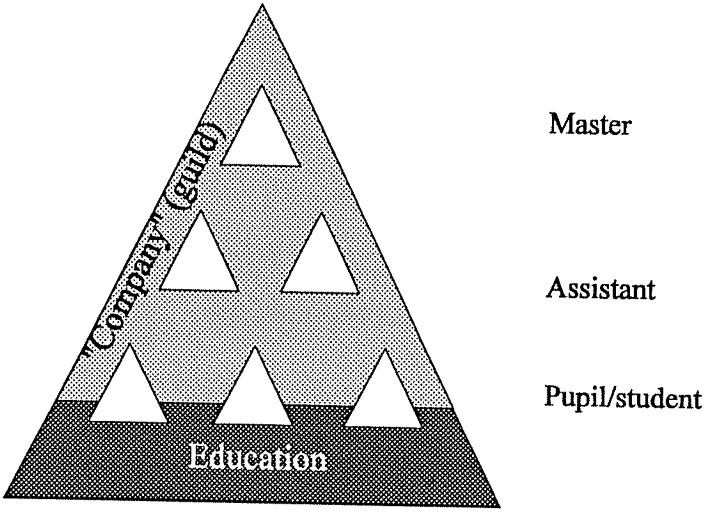

Figure 2: Internal structure in a guild-system.

The table below gives an overview of some of the main characteristics of a guild system.

▪ *Product responsibility*	*Product cost, preformance, quality and reliability are under the direct responsebility of the "master"*
▪ *Hierarchy*	*Based on proven capabilitys on lower levels of organisation, throughout the organisation*
▪ *Education & training*	*Through the hierarchy of the organisation; based on "on the job training" and skills, acquired in the organisation*

1.2 Early industrialisation: separation between education and industry

In the early phases of industrialisation this same structure was maintained only for a short period of time. Due to the difference of scale of the small "companies" in a guild and the much larger first industrial companies, a modification of the traditional structure became necessary. One of the first parts of the traditional structure to change was the educational role that was part of the guild structure.

Because, in many cases, industrial production needed on the production floor labourers with only a limited set of skills, the traditional educational role of the guild soon disappeared. When skills were needed, for example in product development and design, people were not trained in the structure of the company. This training moved to external schools and universities.

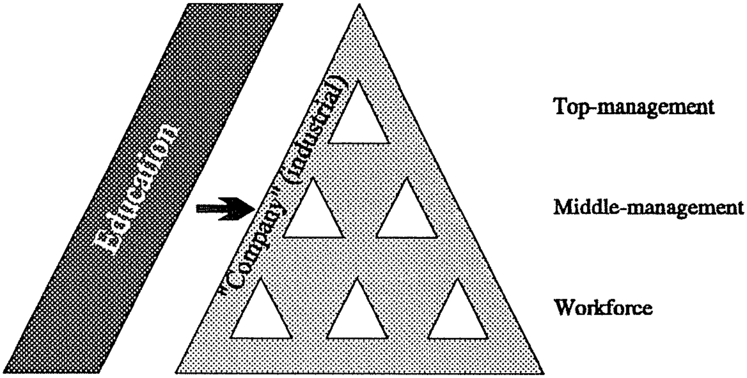

Figure 3: Separation between industry and education

A second difference between the traditional guilds and the modern industrial companies became the strong separation in functions. First this separation became apparent on the level of the work force. Functional specialisation developed, like "development engineers", "production engineers", "factory workers" and "salesmen". This specialisation resulted in a strong separation of responsibilities. The development engineers were responsible for the development of the product, the production engineers were responsible for the development of the production process, the quality and reliability department had the responsibility for the quality and reliability of the product and, finally, the sales force had the responsibility for the product being sold. This structure translated itself also into the management structure of the company. For example: developers reported to development managers who reported to the vice-president for product development. This structure became known as the "functional organisation".

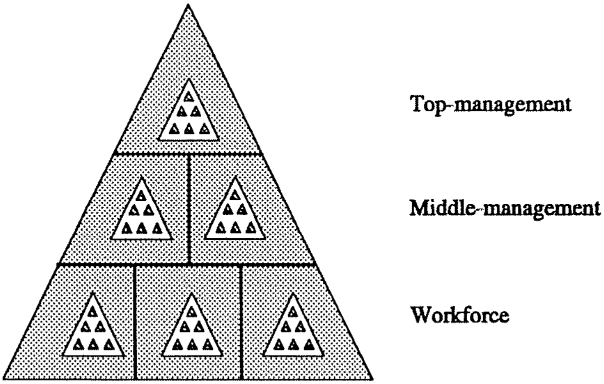

Figure 4: The functional organisation

1.3 The functional organisation: separation between functions

This organisational structure has had considerable impact not only on the development process of the product but also on quality and reliability aspects of the products made in such a process. Basically, the responsibility of developing a product became a sequential process of different departments, each working on their own specialised part of the total process. Due to the higher level of specialisation the development of products with a very high degree of complexity became possible. One of the advantages of the functional organisation was that it allowed for a high degree of specialisation in quite large organisations. One of the disadvantages was that through this high degree of specialisation and the hierarchy, focused on the same functional specialisation, departments became "inward looking". Quite often the best engineer became engineering manager and, eventually, department head of the engineering department.

The table below summarises some aspects of the functional organisation.

▪ *Product responsibility*	*Product planning, development, production and sales under the responsibility*
▪ *Hierarchy*	*Hierarchy, based on the functional (specialised) departments, throughout the organisation*
▪ *Education & training*	*Basic training outside the organisation; further development in the company (through, predominantly, external training) of the specialism involved*

The figure below gives a schematic overview of a development process in a functional organisation.

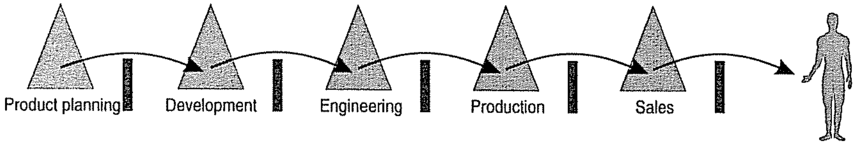

Figure 5: Development processes in the functional organisation

In the functional organisation the final product was a product sequentially optimised to the criteria of all the individual departments. See figure 6. Quite often this lead to sub-optimisation in the various phases of the development process; the product planning department planned projects only achievable with great difficulty, and the development planned features which were very difficult to produce.

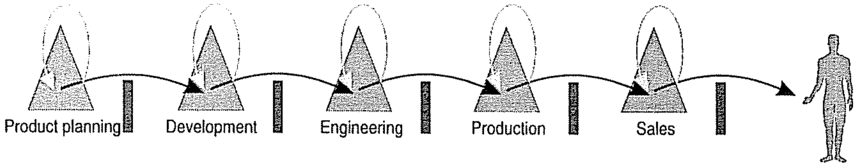

Figure 6: Sub-optimisation in a functional organisation

In this functional organisation product quality and reliability became the responsibility of the quality and reliability department. The main task of such a department was quality assurance; analysing the quality and reliability of completed products by means of testing according to well defined qualification procedures. Although these reliability test acted as a safeguard against un-reliable products the tests often caused considerable delay in those cases where (almost) completed products had to be changed or even re-worked due to insufficient reliability.

2 Current industrial design processes; pressure on time to market profitability

Recently, especially in the last decade, industry shows a strong demand on *throughput* and *time to market-profitability.* The pressure to come on the market with new products in a shorter time has been increasing while the complexity of the products increased as well. An additional problem is that the customers also expected a high reliability of these complex and expensive products. When people buy something with the status of a Rolls Royce (such as a modern high-end television set) they expect also the quality and reliability of a Rolls-Royce. This means that increasingly complex products have to be developed in shorter times with higher levels of quality and reliability. Therefore a classical design cycle where quality and reliability are tested or inspected into a product is no longer feasible. Nevertheless, in practice, most design cycles still show this traditional approach.

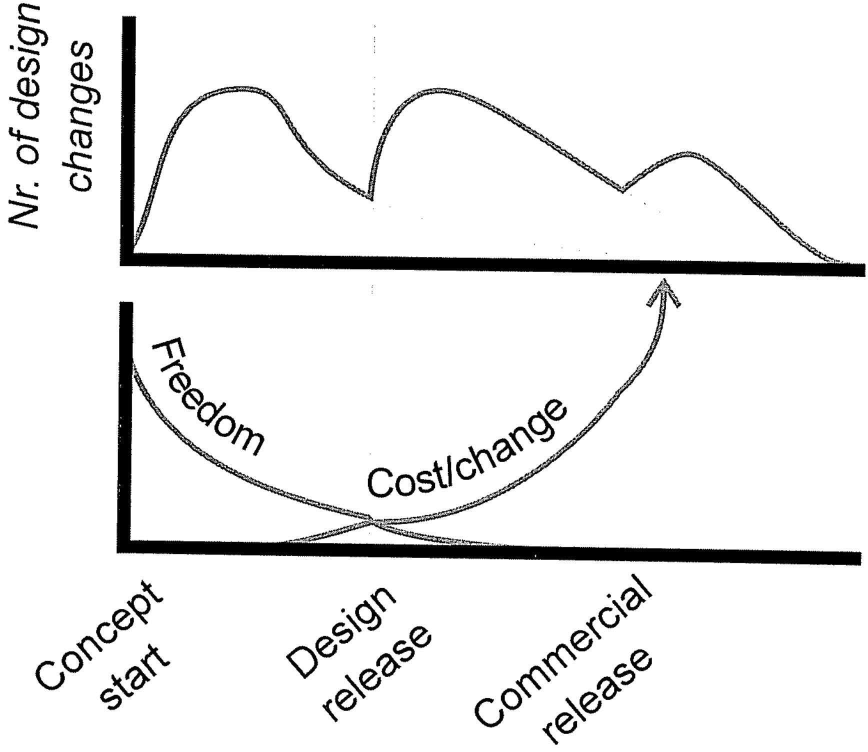

Figure 7: Number of design changes as function of the design processes

Figure 7 shows the number of design changes as a function of the design process. External studies [ASI90] but also own observations [BRO93] show for many design processes that roughly the same number of design changes takes place after the design release of a product as before the design release. It is obvious that early design changes have the advantage of a much greater flexibility for the designer (less is fixed) as well as less cost due to the changes. Early design changes can be introduced by means of a pencil mark; late design changes, especially after commercial release of a product, will require changes in a running production process or, even worse, at the customer via a "market recall" of a product. Stevens [STE93] has shown that roughly 70% of the future price contents of a product is determined in the early phases of the development process while own observations [BRO93] show that 50% of the design changes takes place after design release on a largely fixed design. *Therefore it will be necessary to optimise a product already early in the design process on all aspects; design, engineering, production and customer use.*

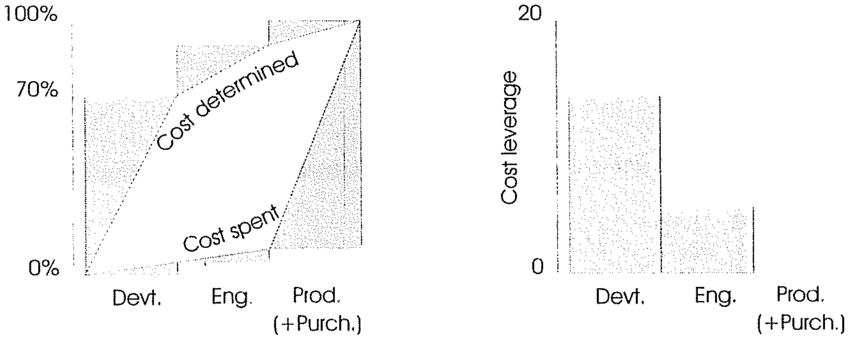

Figure 8: Cost aspects of- and cost leverage on- the development process

2.1 The problem of late design changes; the need for embedded reliability

In order to prevent (late) design changes it will be necessary to derive the backgrounds of the (highly inconvenient and obstructive) changes late in the design process. These design changes occur especially at the major interfaces in the functional organisation;

- *The interface between product strategy and planning on one side and product development on the other side*
- *The interface between product development and engineering production*
- *The interface between production and the final customer*

It is possible to define three causes for the three phases where design changes occur:

- *Concept and design phase: A product is designed in detail, based on the initial product specification, and during this detailed design procedure problems, flaws and conflicts in the specifications become apparent.*
- *Design release: A product is produced for the first time in higher volumes and applied for the first time in larger tests. Differences between an ideal product such as specified at design release in the design specification and (variations in-) actual production, the material used and problems with the use of the product become apparent.*
- *Commercial release: A product is produced for the first time in high volumes and for the first time subjected to the final customer. Differences between an ideal product, such as specified in design specification and (variations in-) actual production, the material used and the actual customer use of the product become apparent.*

All these design changes mean delay in time to market and increase in product cost.

Especially the last and most critical two groups of changes directly relate to unanticipated quality and reliability problems, not taken into account earlier in the design process.

It is not surprising that, at the introduction of “yet another design change”, many people in the development process ask themselves: “Will it really work this time?”

Although current quality and reliability assurance methods have proven their capability produce products with a high standard of quality and reliability, the methods are apparently insufficient to prevent unanticipated design changes, especially in a time where “time to market” is of utmost importance. This means that, although most useful for other purposes, reliability assurance is insufficient in the current design process. Tools are needed for “reliability synthesis”; bringing in reliability in the product synthesis phase. This means that reliability tools have to be used in a predictive way during the product synthesis phase. In order to derive a solution for this problem the next section will explain some backgrounds of quality and reliability and will discuss some of the most common used tools for reliability analysis in the early phases of product development.

3 The challenge: embedding reliability in the early phases of the development process

From the previous sections it is possible to draw three major conclusions:

1. *The quality and reliability of a product are predominantly determined in the early phases of the development process*
2. *The current role of quality and reliability is predominantly an assurance role*
3. *Tools and methods for embedding quality and reliability in the early phases of product development are not available.*

These three points form the basis for a new and challenging area in reliability engineering; both in research and education.. In the next sections I will present some ideas for a roadmap of how to achieve this goal.

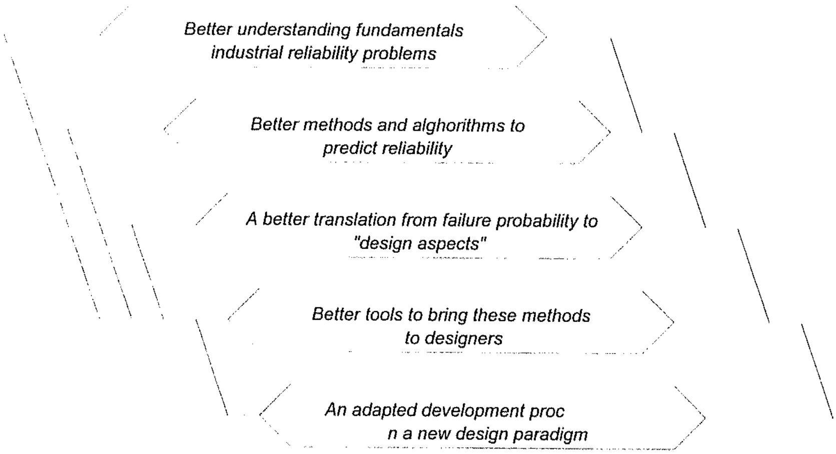

Figure 9: A possible roadmap in order to achieve reliability in early product development

Before explaining the backgrounds of this roadmap it is necessary to understand what quality and reliability is from a customer perspective and how this customer related quality and reliability can be translated to design methods and tools. It will also be necessary to explain why currently available reliability prediction methods are insufficient in the design synthesis phase.

3.1 Traditional reliability definitions

Traditionally quality and reliability are defined as:

- *Quality: the ability of a product to fulfil it's intended specifications*
- *Reliability: the ability of a product to fulfil its intended specifications for a given period of time*

In many cases, especially in consumer products, this statement was translated in:

- *A product is able to fulfil its specifications if all the components of a product are able to fulfil their specifications.*

Simplified: a product works if all the components in the product work. This statement is also the foundation under one of the most common used tools for reliability prediction in the early phases of the development process: parts reliability prediction; more commonly referred to as either parts count analysis or parts stress analysis. The following section will explain this method and will also explain why this method is of little use as a reliability synthesis tool in the early phases of the development process.

3.2 Currently available tools for reliability in the (early phases of the-) design process

One of the best known reliability prediction methods is the method of part failure rate prediction. Since the early fifties handbooks based on this method have been developed for electrical systems (and, more recent, also for mechanical systems) to predict the failure rate of a circuit, construction or system based on the failure rates of the individual components used. The advantage of this method was the easy possibility to translate component failure rate to the failure rate of a complete system.

$$\left.\begin{aligned} R_{system} &= \prod_{i=1}^{n} R_{component} \\ \lambda_{i,\,component}(t) &\approx \lambda_c \\ R_{component}(t) &= e^{-\lambda_c t} \end{aligned}\right\} \Rightarrow$$

$$R_{system} = \prod_{i=1}^{n} R_{component}(t) = \prod_{i=1}^{n} e^{-t.\lambda_{c,i}} = e^{-t.\sum_{i=1}^{n} \lambda_{c,i}} \Rightarrow$$

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

Determining the failure rate of a complete system was possible by adding-up all the failure rates of the individual components in a system. This technique was based, however, on the assumption of constant failure rates. Although many people have observed that this constant failure rate model had certain limitations for early failures (shortly after t=0) and wear-out failures these limitations are usually neglected in failure rate prediction [Bro89a]. See figure 10.

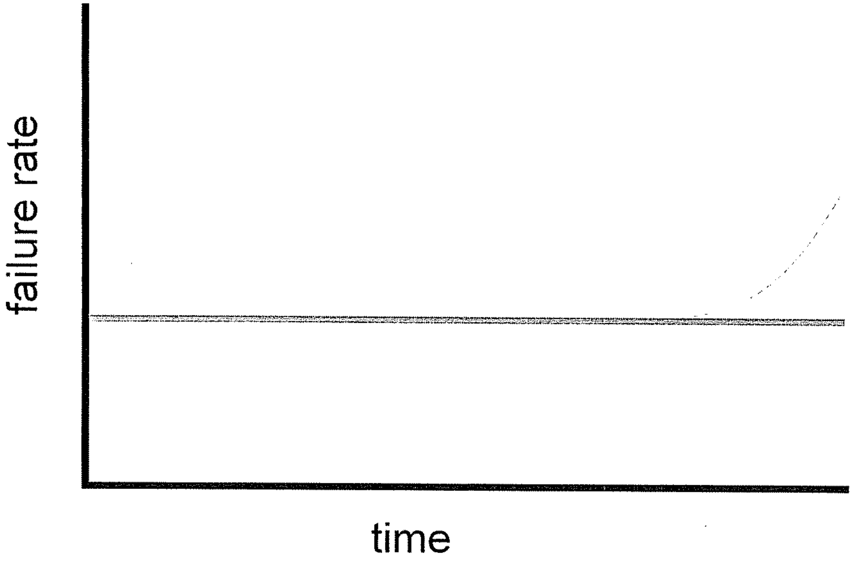

Figure 10: Simplified failure rate model; constant failure rates

Well known handbooks using this method are, for example, the MIL-HDBK-217 [MIL217], British Telecom HRD4 [BTHRD4] and various others. Also many companies have internal reliability prediction handbooks, based on the same principle. Basically these handbooks describe the expected failure rate of a component using the following type of formulas:

$$\lambda_p = \lambda_b . \pi_e . \pi_q . \pi_\_ ....$$

λ_p: part failure rate (failure / hours)

λ_b: part basic failure rate, (via Arhenius law)

π_e: multiplication factor for the environment used (fixed, mobile, ...)

$\pi_\_$: other multiplication factors (speed, analog / digital, ...)

The example below gives an example of the calculation of the basic failure rate of a motor, according to the MIL-HDBK-217.

$$\lambda_{motor} = \frac{t^2}{\alpha_b^3} + \frac{1}{\alpha_w}$$

λ_{motor}: motor failure rate

t: motor mission time

α_b: Weibull characteristic of bearing life constant (mechanical)

α_w: Characteristic life consant of winding (electrical)

The formulas in these handbooks are used under the a number of assumptions:

- *All components, within the same components class and the same application class, are assumed to have identical failure rates*
- *Effects due to manufacturing differences of components (tolerances, flaws) are not taken into account*
- *Components do not mutually influence each other provided that they remain within specification limits.*
- *Components do not change properties with time and are only subject to random failures. (constant failure rate model)*
- *Degradation mechanisms in components are predominantly of a thermo-chemical nature.*
- *The use of a system is assumed to be constant, time independent and depending on the environment class only.*

Practical use of these method shows that differences between predicted failure rate and actual failure rate of several orders of magnitude, both too high and too low are found in practice. [BRO89b] [BRO92a]

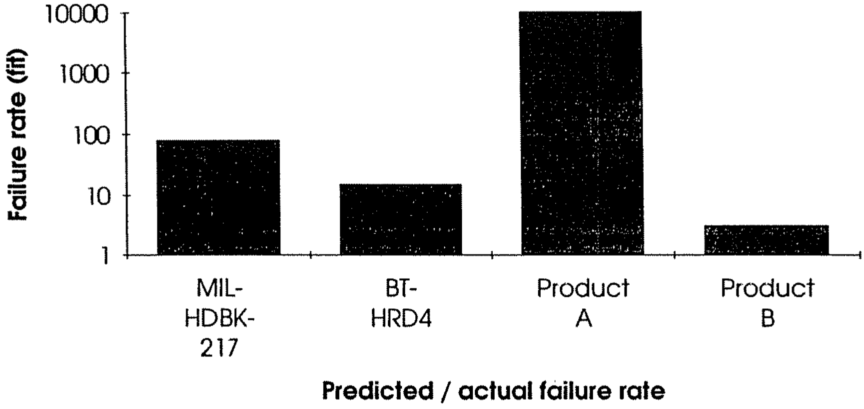

Figure 11: Predicted (MIL, BT) versus actual (A, B) failure rates

Summarising it is possible to come to the following conclusions:

- *There is a strong need for "building-in" quality and reliability in the early phases of product development*
- *The methods most commonly used have a too high degree of uncertainty to be used in industry*

From this I would like to put the following challenges for reliability *research*:

- *Better understanding of the backgrounds and fundamentals of (industrial) reliability*
- *Defining methods, tools and algorithms to translate these fundamentals to (industrial) design processes*
- *Supporting adaptations of current industrial design processes towards processes that allow "inherently built-in quality and reliability"*

The following sections will explain these challenges more in detail.

3.3 Needed: better understanding of reliability fundamentals

Recent studies [CON87] [BRO90] [WOL93] have shown that there is not such a thing as a "constant failure rate curve". As explained in the previous section attempts to correlate this model to actual field reliability have completely failed not one but in many cases.

A more detailed analysis of the failure rate curve has shown that the failure rate curve consists of four sections.

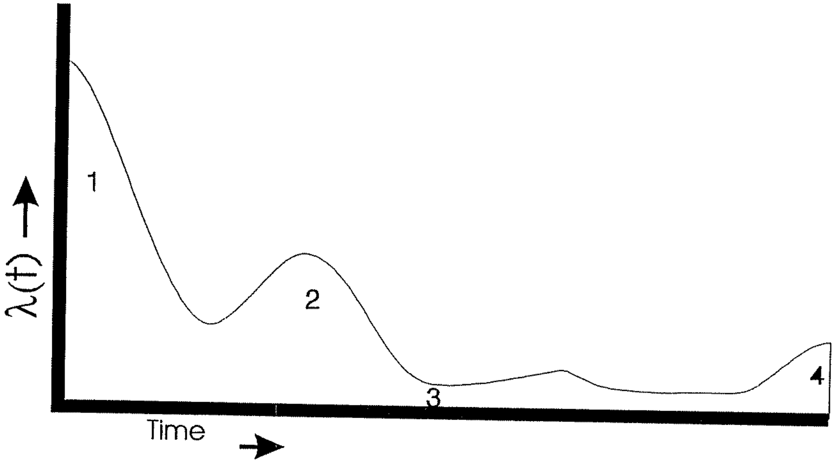

Figure 12: Four-phase failure rate model

In order to explain the four-phase failure rate model the concept of stressor/ susceptibility analysis has been developed. [BRO92a]. This model bases itself on the probability of activation of failure mechanisms in systems. Although many aspects of quality and reliability, as observed by the customer, are very similar in appearance quality and reliability problems as described above can emerge due to a number of different basic failure mechanisms or causes. An overview is given in the table below:

	Time independent	Time dependent
Functional failures	The product does not fulfil its functional specifications at the moment of delivery	The product does not fulfil its functional specifications after a certain period of use
Physical failures	The product shows physical failures at the moment of delivery	The product shows physical failures after a certain period of use

As mentioned in the previous sections these problems can happen at the major population of ‘nominal” products, or, only at a certain sub-population.

this leads to the following "family" model of quality and reliability problems: see figure 13.

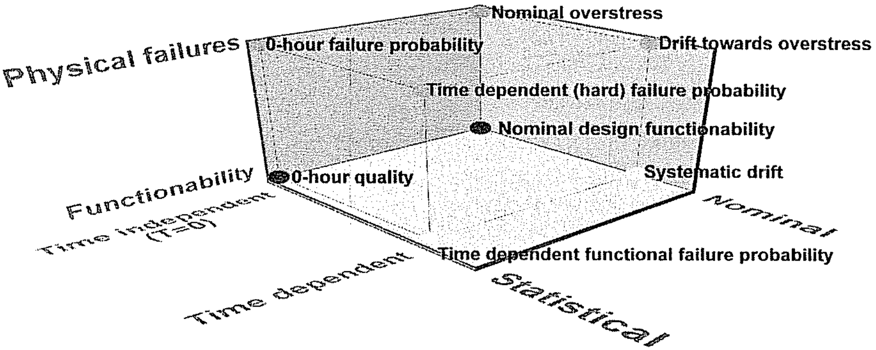

Figure 13: Basic aspects of Quality and Reliability

From figure 13 it is possible to define the following eight aspects of "customer quality and reliability" as a function of three basic domains. Aspects:

1. *Nominal design functionability*
2. *Nominal overstress*
3. *Systematic functional drift*
4. *Drift towards overstress*
5. *Zero hour statistical design functionability (quality / yield)*
6. *Zero hour statistical failure probability (quality / yield)*
7. *Time dependent statistical functional failure probability*
8. *Time dependent statistical physical failure probability*

Although traditionally mainly the last point is considered in reliability analysis, from a customer perspective all these aspects contribute to the quality and reliability of a product. All these aspects are a function of three basic domains:

Aspect	Effect category	
1. Failures types	- Functionability	- Physical failures
2. Time	- T = 0	- Time dependency
3. Statistics	- Nominal level	- Statistical level

This concept forms the basis of reliability prediction using stressor/ susceptibility analysis.

This methods bases itself on the analysis of physical or functional failure mechanisms in structures in the domains described above. It models reliability using the susceptibility of failure mechanisms in individual components for (combinations of-) stress factors or stressors.

As a result this method will not only cover a constant failure period but also failures in early life of a system as well as wear-out failures.

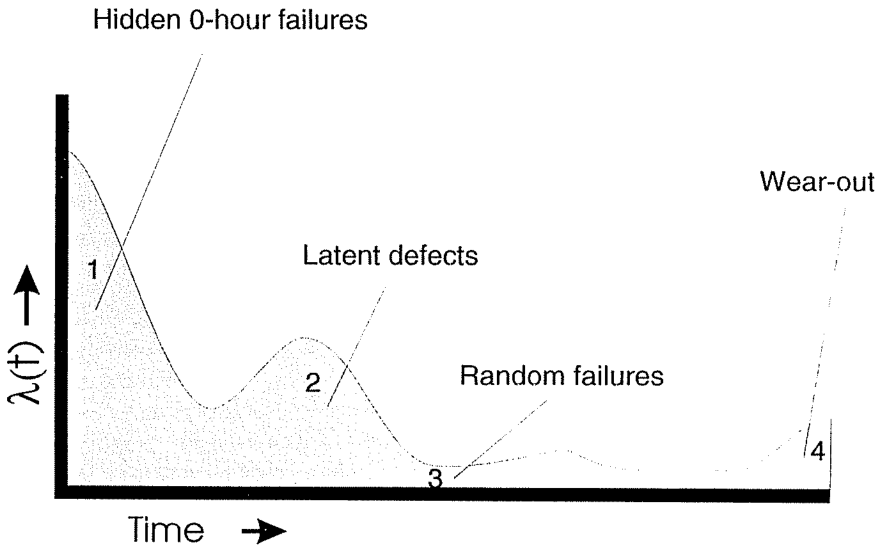

Figure 14: relation roller-coaster curve stressor/susceptibility interaction

1. ***Hidden 0-hour failures**: Failures at or shortly after t=0: products, either failures during production or immediately after production. Products failing in this period have in many cases escaped the test program.*

Products failing in operation (almost) immediately are often due to either component flaws (weak components) or extreme stresses due to, for example, insufficient tolerance analysis.

2. ***Latent defects/early wear-out**: (Early) Failures shortly after t=0: similar to 1; products delivered with either increased stresses (due to e.g. material tolerances or tolerances in use) or component flaws (or both). Due to the increased (relative) stress there is not the immediate danger of failure but a largely increased probability of accelerated degradation. After a certain time interval of degradation this may lead to a largely increased probability of failures (the second hump in the failure rate curve).*

3. ***Random failures**: At the moment all sub-populations, within a (large) batch of products, with either initial failures, increased (relative) stress or increased degradation have died-out. At a certain moment in time there will remain a population with a fairly homogeneous (relative) stressor/ susceptibility interaction. This will result in a failure probability which is to a certain extend constant in time. Quite often the stressor probability density function is, in this interval, governed by external random effects such as lightning, mains transients etc.*

4. ***Systematic wear-out**: Basically this part of the curve shows a strong similarity with the second part of the curve (early wear-out). In this case (long term) degradation and (long term) drift cause increased probability of failure. As the population of (remaining) products is, at this interval in time quite homogeneous (see also the section on stable systems)*

This means that the concept of stressor/susceptibility analysis is able to explain not only the old, constant failure rate model but also the more recent four-phase roller coaster curve in one comprehensive model. The model, however, has at this moment the status of a mathematical concept. This mathematical concept will need to be extended further in order to allow practical predictability of the time dependent failure rates of products in the early phases of the design process.

This is, ladies and gentlemen, one of the main challenges for research on reliability fundamentals in the future: better predict reliability

- *on the level of nominal products as well as taking into account product statistics*
- *on the level of time-independent phenomena as well as on the level of*

time-dependent phenomena

- *on the level of physical failures as well as on the level of functional failures*

3.4 Needed: a translation from failure probability to design aspects

In order to bring new forms of reliability analysis into the process of designing a product it will be necessary to understand what design aspects translate to reliability.

The concept of stressor/susceptibility analysis provides a framework which allows reliability analysis of mechanical systems based on the individual failure mechanisms in the product. The method itself, however, is at this moment interesting for reliability engineers but still of little practical value for the designers of mechanical systems. Although this method is able to translate basic failure mechanisms to failures on the level of a complete system in the form of a time-dependent failure rate, this analysis method requires quite detailed knowledge of the statistics of production processes and material aspects that determine these failure mechanisms. What is needed in the future is an extension of this framework to the process of designing.

This because of the fact that many designers of systems and designers of the systems where the systems are used will have no time available to consider every single failure mechanism in every single part of a structure. Most important points for a designer will be:

- *Are any failure mechanism in a construction or system activated*
- *If yes: with what probability*
- *With what parameters on (construction/system) designer level is it possible to influence / optimise the probability of activation of the mentioned failure mechanism*

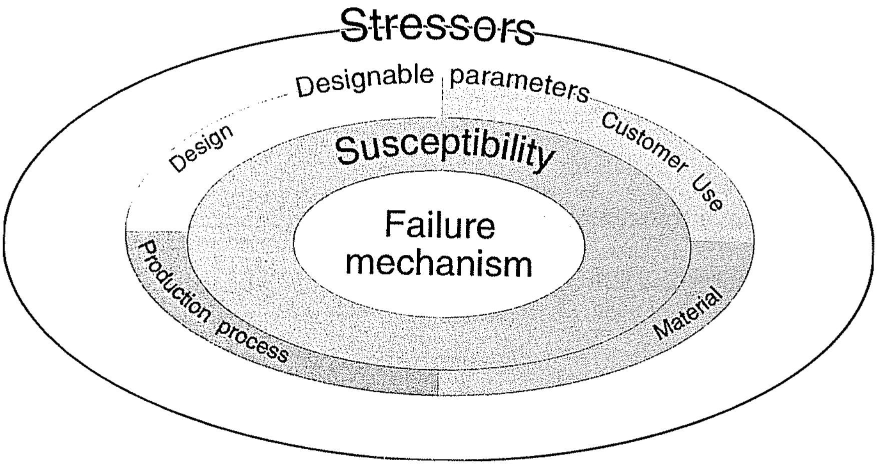

Figure 15: Need for relation from stressor/susceptibility analysis to designable parameters on various levels

3.4.1 Step one: translating material knowledge to susceptibility models.

One of the first requirements to come to better reliability prediction requires the development of susceptibility models. The development of these susceptibility can make use of the accumulated knowledge in materials science. People working in materials science have been working to study the relation between external influence factors and material properties. Although material science provides a tremendous foundation for the development of susceptibility models this does not mean that susceptibility models are readily available. Studies, for example by Wolbert [WOL93], show that the development of a susceptibility model for a relative simple material structure such as a solder connection can be a considerable effort. Therefore I would like to invite all my colleagues in material science to join in this effort of developing susceptibility models. I also would like to invite my colleagues working on equipment for processes to translate their knowledge on the statistical behaviour of processes to the statistical aspects of susceptibility models.

3.4.2 Step two: deriving stressor models.

A second requirement for the reliability prediction using stressor/susceptibility interaction is the availability of stressor models. A stressor model describes statistically the combination of external stress factors influencing the probability of activation of a failure mechanism. In most cases it is not possible to derive such a stressor model analytically. Often the number of parameters is too large and the (statistical) interaction between the parameters too complex. One of the easiest methods to derive a stressor set in research is by making use of one of the well-known techniques for statistical hardware experiments:

- *Taguchi experiments [TAG86]*
- *Shainin experiments [HAR90]*
- *Traditional Design of Experiments*

There is, however, a problem in analysing, during product development, in this way structures such as complex mechanical systems. At the moment actual moulds are available the design is, most times, fixed to such an extend that major design changes are in many cases not practical. An alternative for hardware experiments can be found in computer simulation.

Quite successful experiments have been carried-out to derive stressor-sets using finite element techniques. A disadvantage of using FEM is that this analysis technique is, even for nominal analysis, computational intensive. Extending a computational intensive technique to the domain of statistics severely increases this problem. At this moment a combination of Monte Carlo analysis and Finite Element analysis is used to derive stressor sets for in products. This method combines two computational difficult methods into something that is something close to a numerical nightmare.

Therefore I would like to invite my colleagues working in mechanical simulation techniques and my colleges working in the field of statistics to join in the development of new techniques or enhancements of currently available techniques in order to come to an efficient prediction of stressor-sets.

One of the most promising emerging areas is the modification of existing Monte Carlo algorithms.
See figure 16.

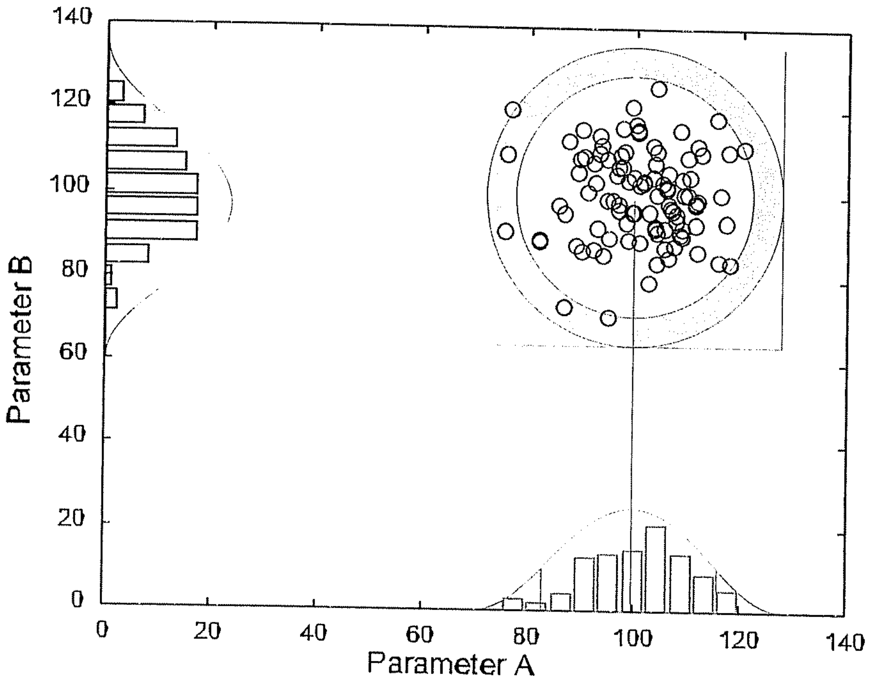

Figure 16: Modification of Monte Carlo analysis, concentrating on extremes

At this moment in doing statistical analysis using Monte Carlo methods the main attention is focused on products with the most likely combinations of parameters. (The centre in figure 16.) As mentioned earlier for reliability prediction not this “quasi-nominal” population is the most important but especially “extreme” sub-populations. Obtaining an accurate prediction of the reliability behaviour of a population with a reliability demand of no more than 0.1% failures in the first year of use will require often more than ten thousand simulations, each of which may take over an hour to perform. Recent work of Spence and Nelder, in which we participate via an industrial partnership program, concentrates especially on techniques to predict in a more efficient way the probability of occurrence of extreme combinations of parameters and their effect on product performance. (The circle in figure 16.) Of course in a multi-dimensional non-orthogonal parameter space this circle will have a slightly more complex shape. This modified Monte Carlo analysis appears to be a promising approach for a more efficient reliability prediction.

3.4.3 Step three: translating failure probability to designable parameters

Reliability analysis and optimisation requires not only a more accurate prediction technique but also a translation to domains where the designer has direct (or indirect) influence. As a result an early optimisation of reliability and quality should at least consider the following aspects on a statistical level: analyse and optimise, as integrated part of the design of a product the concept of a product as a function of the:

- *design itself*
- *the material that will be used*
- *the future production processes*
- *the expected customer use*

See also figure 17.

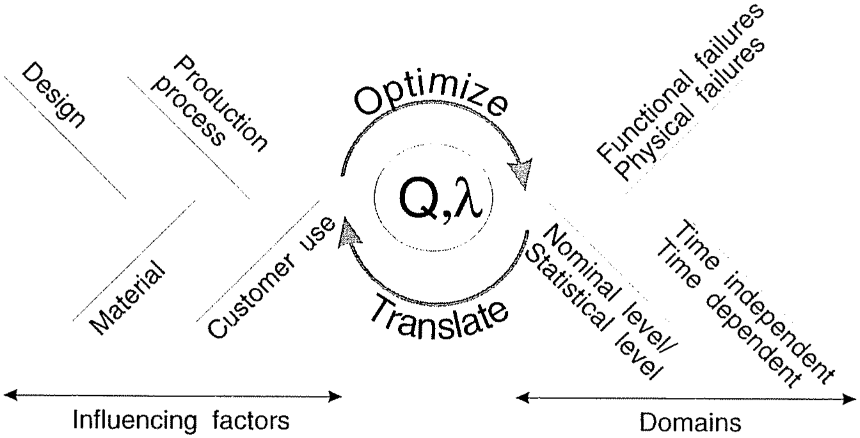

Figure 17: Basic aspects determining quality and reliability

A simulation system for computer aided quality and reliability simulation should fulfil the following requirements:

- *The system should be able to perform stressor/susceptibility analysis on all major failure mechanisms in mechanical structures.*
- *It should derive from the mentioned analysis results components or*

structures with increased failure probability

- *It should derive for the structures with increased failure probability all related parameters, on the level of the system design, the production processes, the material and customer use.*
- *There where parameters are designable (mainly in the system design but in some cases also in the process design) the system should give guidelines for optimisation of the product towards robustness.*

Using computer simulation for stressor/susceptibility analysis it is possible to determine the probability of failure of a certain failure mechanism in a given component. As mentioned in the previous paragraphs for a designer it will also be important to analyse what parameters in his design dominantly influence the probability of failure of the (dominant) failure mechanisms.

In the next step it is determined whether there is a systematic shift in the output parameters for a shift in input parameters. Although the, as a consequence of the Monte Carlo process, the output parameters will show a random characteristic it is possible to determine two important aspects:

- *the correlation between variations in output parameters and variations in the various input parameters*
- *the statistical or tolerance sensitivity of output parameters for the various input parameters [SPE88]*

It would require to much time to concept the concept of statistical sensitivity in detail at this moment. At this moment the technique provides a successful translation from failure probabilities to the most dominant design aspects. research in this area mainly concentrates on decreasing the number of simulations required to achieve a certain level of confidence and on the use of non-linear aspects in products and materials.

3.5 Needed: new tools

The next step in mechanical reliability analysis will be to establish a link between a (computer aided) mechanical design system and the program performing this analyse. This link should consist of a system that is automatically able to translate the information contained in the description of the mechanical construction into the required set of mathematical equations. Such a system could consist of the following layers:

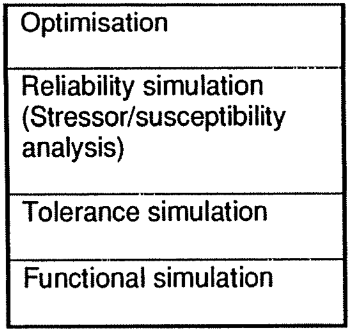

Figure 18: Hierarchy in mechanical quality and reliability simulation system

3.5.1 Functional simulation

The first level of the simulation system consists of functional simulation. Many of the stressors relevant for the earlier mentioned failure mechanisms can be derived from mechanical simulation of the geometric description of the system.

3.5.2 Tolerance simulation

As mentioned earlier one of the key-reasons for design changes late in the design process are observed differences between the designed nominal product and the actual product produced or used in high volumes. Therefore a realistic prediction of reliability for a high-volume product will require simulation, not only of an ideal product used under ideal user conditions but will also require analysis of the expected variability of the expected stressor/ susceptibility interaction.

In this phase often detailed knowledge about the used materials and production processes is required.

3.5.3 Reliability simulation (Stressor/susceptibility analysis)

This layer uses the earlier derived tolerance simulation to derive stressor sets relevant for failure mechanisms in the components used. It is important that the system has possibilities to simulate effects of nominal stressor probability density functions and nominal susceptibility functions for the failure mechanisms but also to simulate the effects of both tolerances in stressor sets and tolerances in susceptibility parameters.

3.5.4 Optimisation

The top-layer of the system is used to identify all parameters with a high impact on the probability of activation of the mentioned failure mechanism. This information is used to propose a new set of component parameters which should give a decreased probability of failures.

The table below gives an overview of the current status of the system and the way still to go.

R: Available on research level
O: Available on operational level
—: Not available
-: Generally not available
±: Often available
+: In most cases available
++: Available

	Tools	Models	Parameters
Optimization	R	NA	NA
Reliability simulation	R	R	R
Tolerance simulation	O(+)	O (-)	O (--)
Functional simulation	O(++)	O (+)	O (±)

Although still in an experimental phase computer simulation has given us already in several pilot projects a very good possibility to analyse in an early phase of the development process quality and reliability aspects of both static and dynamic mechanical constructions. It is, at this moment, possible to introduce required functional criteria plus criteria relating to the following failure mechanisms:

static
- *breaking of most metals*
- *breaking of many plastics*

long-term dynamic
- *degradation of metals (fatigue)*
- *degradation of many plastics*
- *wear-out of several bearings*
- *long-term deformation of many plastics*

For the near future the research will concentrate on the translation of results of research on detailed failure mechanisms into susceptibility models as well as on the adaptation of the simulation system to derive the related stressor sets. Although used at this moment, predominantly in high volume consumer products it is also possible to apply the mentioned analysis methods in other industrial areas such as process industry where the analysis mentioned is being extended to functionability, quality, reliability and safety.

The next step in mechanical reliability analysis will be to establish a link between a (computer aided) mechanical design system and the program performing this analysis. This link should consist of a system that is automatically able to translate the information contained in the description of the mechanical construction into the required set of mathematical equations.

4 Needed: a new industrial design paradigm

The reason, ladies and gentlemen, why I started this presentation with a discussion on the history of development processes is that, even if the research described in the section above is highly successful and industry does not change the current functional structure, the results of the research will have little or no value for industry. As mentioned in the initial sections of this document, in an organisation where there are strong and strict separations between sections in an organisation the main performance indicator for development engineers will be achieving a certain functionality with minimum cost in the shortest possible time. Problems relating to quality and reliability of a product might be relevant for a development engineer from a philosophical point of view but will in practice have very little priority.

Therefore it is suggested to adopt a new design paradigm, a design paradigm based on predictability. In a predictable organisation designers are no longer judged on the fact whether they achieve a certain function within the allowed cost-time frame. This classical approach has lead, in the classical functional organisation, to in the best cases an indifferent attitude towards quality and reliability and in the worst cases a reluctance.

In the proposed predictable organisations development teams are judged on their ability to predict the functionability, quality and reliability of their product[1]. In order to achieve this goal a very close co-operation between the various disciplines is not only recommended but strongly required. If a

[1] *Ultimately this concept could be extended to making a team responsible for the profitability of a product*

development team needs to predict the reliability of a product based upon unknown material characteristics they will need to discuss in detail with the supplier of the material. Basically people working in a predictable organisation could use a three step approach.

1. *Define the key parameters or characteristics of a product*
2. *Predict the performance of the product in terms of functionability, quality and reliability*
3. *Judge the actual performance versus the prediction in order to improve future prediction capabilities*

This leads to the structure indicated in figure 19.

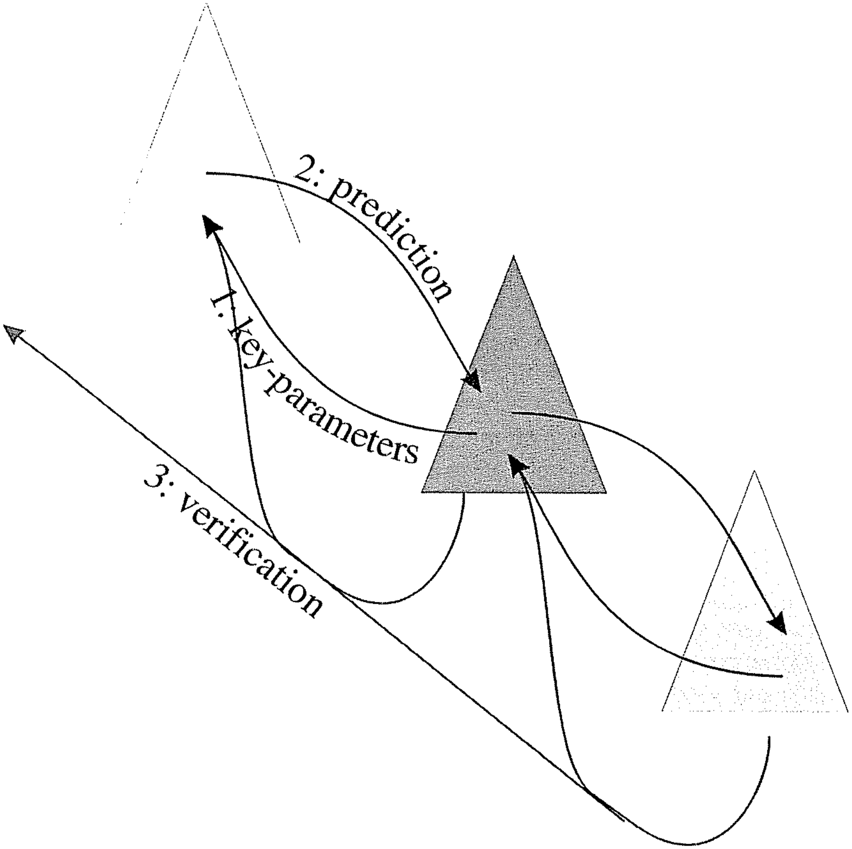

Figure 19: Basic information flow in a "predictable" organisation.

This concept can be applied throughout the product development cycle. Extensions towards the non-technical sections of this cycle are not only possible but even highly desired. [BRO92b] Due to the requirement to work closely together in order to come to predictability people working using this approach do not act as a sequence of different disciplines but as an integral "project team". See figure 20. This brings the way of working back to the structure used in the old guild system. First experiments with this way of working have shown that it can lead to considerable successes, leading to:

- *Less, unpredicted, design changes*
- *A shorter development time*
- *A better and more predictable product quality and reliability*

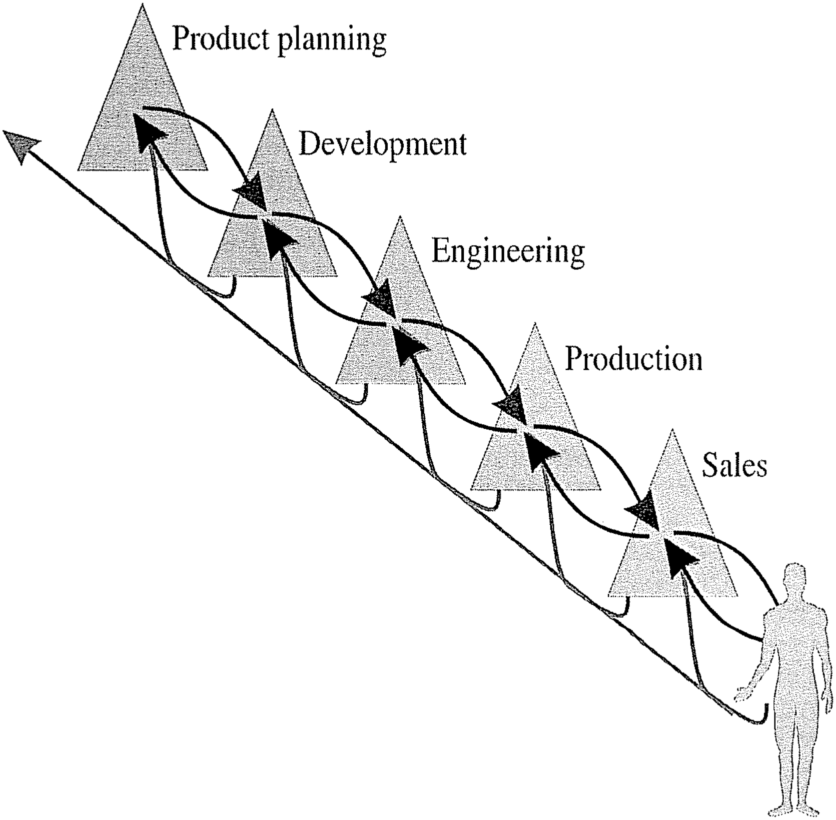

Figure 20: The predictable organisation

These first experiments, however, were carried out only on a small scale. Translation of these first experiments will require further research. Therefore I would like to invite my colleagues in industrial engineering and business economics to join on the further developing of the predictable organisation.

5 Needed: education in line with new industrial design processes

At this moment both research and education in universities reflect the functional structure of industrial organisations. As well as in the industrial functional organisation the functional structure in universities into various disciplines allowed a very high degree of specialisation. For (fundamental) research this structure has shown tremendous benefits which will not be further discussed here.

In the old, functional industrial organisation this model fitted also quite well. Students in universities, who wanted a career in product development, followed courses in one of the engineering sciences. After completing their studies they were employed by a company where they worked in development departments together with specialists in the same field.

In the new design paradigm this educational structure can provide major problems. People working in product development now have to co-operate with people from many other disciplines. The problem is that people are not able to talk each others language and understand each others problems. People working in product development do not understand the essentials of production processes.

In this respect the educational system in countries like Japan is better adapted for this purpose. In the past I coached students who went to Japan for their practical training. I have to admit that I was completely amazed when a university student in electrical engineering was put to work in a production environment. I even suggested the student to contact his Japanese supervisor for a different job, more related to electrical product development, which the student did.
After a couple of weeks the student was indeed transferred to a development department. What we did not understand is that the Japanese educational system is to a high degree adapted to working in cross-functional structures. Before people are put to work in a development team they have worked, either as part of their university training or as part of the industrial training following university in departments throughout the whole process,

from production up to product development or research.

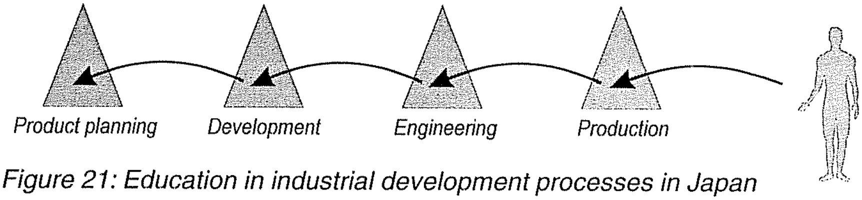

Figure 21: Education in industrial development processes in Japan

I do not say that we have to copy the Japanese scheme to our educational system. It is however important that people who will have the major influence in determining future industrial products know what processes are used in developing products. This means in a technical sense: how industrial production processes work, how these processes lead to components, how these components lead to products and how the products are finally used by customers. This means in an organisational sense: how different specialisms in an organisation can work together in order to achieve predictability. This could be one of roles of education in quality and reliability. As I mentioned in discussing research in reliability engineering where one of the most important roles is, in may opinion, to form a bridge and a translation between various disciplines. The role of reliability engineering in education could be preparing future engineers to cross that bridge, not being hampered by organisational walls.

Ladies and gentlemen, there is a lot of work to do, both in research and education. I hope that the results of this work, both in research and education, will allow future designers, working in industry, to answer future questions like: “Will it really work this time?” with a confident “Yes, of course it will!”.

6 Acknowledgements

At the end of this lecture I would like to express my gratitude, first of all to the Technical University of Eindhoven and the faculty of Mechanical Engineering for putting confidence in me in giving me this opportunity. I also wish to thank my colleagues in the group WOC, especially my direct colleagues Elly, Hans, Henk, Will en Willie, for a most pleasant co-operation. I can only hope that we can continue to work like this in the future.

I wish to thank the management of Philips in giving me the opportunity to

combine university and industry. I wish to thank all my colleagues at Philips, especially the people working in the Quality Engineering group. As most of you will recognise the lecture today reflects ideas that are a result of our joint efforts. We are all faced with a most challenging job in a sometimes hectic environment.

I wish to thank the people of the group BSC of the University of Twente for the opportunity they gave me to start to work in the area of reliability. I wish to thank the students I am working with and who have been working with me in the past. The discussions with you where essential in formulating the goals presented here. I want to ask you to join to bring the challenges presented today into reality in the future. I wish to thank all the people I am working with and I have been working with in the past, in industry and university; colleagues and former colleagues, people working in companies like Analogy, the former HCS, GTI, and Factory Mutual. I want to thank Rolf Spiker for the discussions that have lead to this presentation.

A special word of gratitude I would like to express for my tutors over the years. Wil Peeters suggested me to work on reliability. Jan van't Loo and Tony Harris learned me what industrial reliability means. Highly learned Herrmann, Spence and Verwey, you learned me how to do research in this subject. I hope we can continue and expand our pleasant co-operation in the future.

Finally I would like to thank my family; my parents because of their help and support and, last but not least, my wife, Ineke, for your continuous support, your patience and for all those times I said "just another five minutes".

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