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SIMULATION, A TOOL FOR DESIGNING-IN RELIABILITY

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SUMMARY

This paper describes a new method for the analysis and optimization of reliability as an integrated part of the design process of electronic circuits. It bases itself on the analysis of the susceptibility of failure mechanisms in components as a function of the combinations of external stress factors (stressor-sets). The paper describes the backgrounds of stressor-susceptibility analysis, the need for this analysis and the way this method is used for high-level design and optimization of electronic circuits.

KEY WORDS Stressor-susceptibility analysis Component failure mechanisms Design optimization High-volume consumer electronics

INTRODUCTION

At present industry shows a strong demand for quality and reliability to be built in to the design process of electronic circuits. Owing to the strong demands on throughput and time to market profitability there is a strong need for both short design times and high levels of quality and reliability. Therefore, an (often traditional) 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 1 shows the number of design changes as a function of the design process. Not only external studies,[1] but also our own observations show for many design processes that, generally speaking, 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. Therefore it will be necessary to optimize quality and reliability already early in the design process. This paper describes

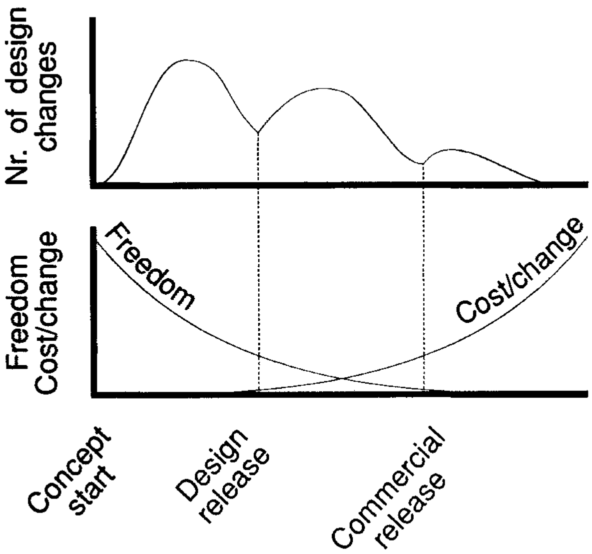

Figure 1. Number of design changes as a function of the design processes

(a) basic problems that will relate to field quality and reliability problems
(b) traditional methods that are commonly used

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to approach these problems and why they do not work
(c) a translation from the basic problems to 'designable parameters'
(d) possible ways to implement this translation into design methods (hardware experiments, computer simulation)
(e) computer-aided quality and reliability simulation.

BACKGROUNDS OF RELIABILITY PROBLEMS

In order to prevent late design changes it will be necessary to derive the backgrounds of especially the changes late in the design process. Generally speaking it is possible to define three main causes:

(i) changes due to a mismatch between expected functionality and achieved functionality
(ii) changes due to a mismatch between expected reliability and achieved reliability
(iii) changes due to changed specifications, for example due to changed commercial insight/demands.

As the third aspect is outside the scope of this paper, we will concentrate especially on the first two items. The two points in time showing a sudden increase in design changes correlate with points in time where the following information becomes available:

1. 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 in the design release and (variations in) actual production, the material used and the test use of the product become apparent.
2. 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 the design release and (variations in) actual production, the material used and the actual customer use of the product become apparent.

Although many aspects of quality and reliability are very similar in appearance quality and reliability problems can be due to a number of different basic causes. Examples are:

1. The product does not fulfil its functional specifications at the moment of delivery.
2. The product shows physical failures at the moment of delivery.
3. The product does not fulfil its functional specifications after a certain period of use.
4. The product shows physical failures after a certain period of use.

These phenomena can occur both at the level of a nominal product or on one or more products in a large series. For a comprehensive model of quality and reliability see Figure 2. From Figure 2 it is possible to define all the following aspects of quality and reliability as a function of the three basic domains given in Table I:

(a) nominal design functionability
(b) nominal overstress
(c) systematic functional drift
(d) drift towards overstress
(e) zero hour quality/yield
(f) zero hour failure probability/yield
(g) time-dependent functional failure probability
(h) time-dependent physical failure probability

Analysis of quality and reliability should therefore consider all the basic areas mentioned above. Optimization requires not only analysis results covering the domains mentioned but also a translation to domains where the designer has direct or indirect influence. As a result an early optimization of reliability and quality should at least consider the following aspects on a statistical level: analyse and optimize, as an integrated part of the design of a product, the concept of a product as a function of:

(a) the design itself
(b) the material that will be used
(c) the future production processes
(d) the expected customer use.

See also Figure 3. This results in a strong need for methods that can be used as integrated part of the early design process.

COMMONLY USED TRADITIONAL RELIABILITY METHODS

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 to predict the failure rate of a circuit or system based on the failure rates of the individual components used. Well known handbooks are, for example, the MIL-HDBK-217,[2] British Telecom HRD4[3] 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 formula:

$$\lambda_p = \lambda_b \; \pi_e \; \pi_q \; \pi_- \; \ldots$$

where λ_p is the part failure rate (failures/h), λ_b is the part basic failure rate (via Arhhenius law), π_e is the multiplication factor for the environment used (fixed, mobile, etc.) and π_- represents other multiplication factors (speed, analogue/digital, etc.).

These formulae are used under the following assumptions:

1. All components, within the same components

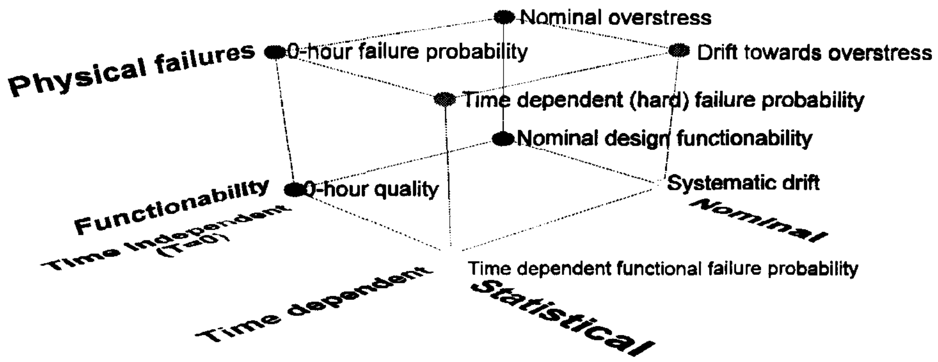

Figure 2. Basic aspects of quality and reliability

Table I.

Aspect	Effect category	
Failures	Functionability	Physical failures
Time	$T = 0$	Time dependency
Statistics	Nominal level	Statistical level

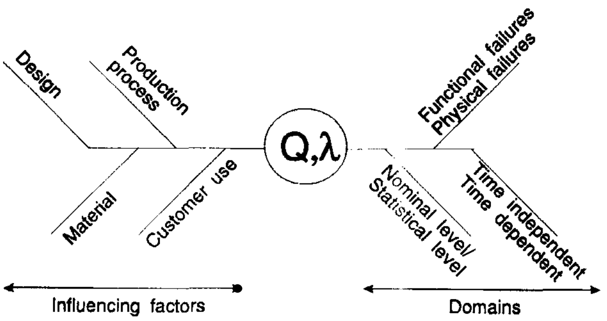

Figure 3. Basic aspects determining quality and reliability

class and the same application class, are assumed to have identical failure rates (example: all low-power commercial switching *NPN* transistors, used in a ground mobile environment at the same temperature, within their specifications, have the same predicted failure rate).

2. Effects due to differences between components within a class are not taken into account.
3. Effects due to manufacturing differences of components are not taken into account.
4. Components within an application are assumed to be, to a large extent, independent.
5. Components do not mutually influence each other provided that they remain within specification limits.
6. Components do not change properties with time (exception: electromechanical components).
7. Components are only subject to random failures (constant failure rate model).
8. Degradation mechanisms in components are predominantly of a thermo-chemical nature.
9. The use of a system is assumed to be constant, time independent and depending on the environment class only.

Practical use of these methods show 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.[4]

Another difficulty is that the methods used provide little relation to designable parameters; in most cases the only aspect that is of use for designers is the component's temperature. The effect, however, of extreme temperature derating remains in many cases within the earlier mentioned uncertainty of the prediction results.[4]

Therefore, the main use of the traditional parts-count reliability prediction methods mentioned remains in the comparison of classes of systems using certain classes of components.

For a more detailed analysis/prediction of the reliability of a circuit or system new methods have been developed.[4] These methods base themselves on the analysis of physical failure mechanisms in components. The analysis in these methods is based on the susceptibility of failure mechanisms in individual components to (combinations of) stress factors or stressors. Using this method it is possible to analyse reliability at the level of single circuits, taking into account

(a) dynamic stresses
(b) differences in stress due to component tolerances
(c) differences in stress due to tolerances in component susceptibility

As a result this method will not only cover a constant failure period but also failures in the early life of a circuit as well as wear-out failures. The next paragraphs will describe the mathematical basis of stressor/susceptibility analysis and will describe how this method can be used to link low-level physical failure mechanisms to the level of 'designable parameters'; parameters where a circuit designer has direct influence to optimize reliability.

A TRANSLATION FROM BASIC PROBLEMS TO 'DESIGNABLE PARAMETERS'

The lowest, physical, level to consider failures in electronic components is the level of failure mechanisms. At this moment considerable research is carried out to better describe and understand these failure mechanisms. Although the various failure mechanisms are often very different in nature it is possible to generalize most failure mechanisms to a common mathematical description.

In this paper we will assume that all failure mechanisms are influenced by (combinations of) stress factors or *stressors*. The combination of all non-redundant parameters influencing a single failure mechanism is called the stressor set* of this failure mechanism. A stressor set is the comprehensive description of all combinations of parameters influencing a failure mechanism.

The probability of activation of a certain failure mechanism is not only determined by the stressor set of this mechanism. Two comparable devices, subjected to the same stressor set can have different failure probabilities due to different *susceptibilities* to this stressor set. Mathematically susceptibility is defined as the probability that a device, under a given stressor set, will fail within a given interval of time (see Figure 4).

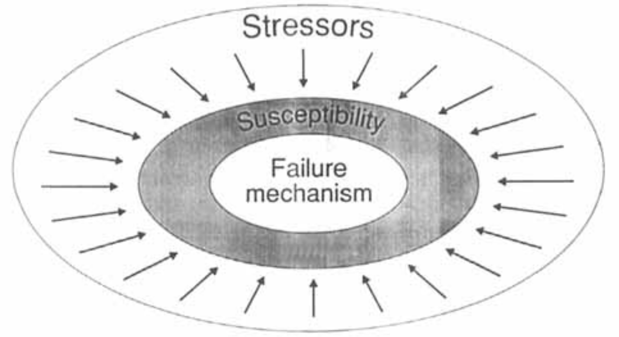

Figure 4. Stressor/susceptibility interaction

Using this concept it is possible to describe very different failure mechanisms in one single concept. The only requirement is a model, describing the susceptibility of a failure mechanism in relation to the associated stressors.

SINGLE EXAMPLE OF STRESSOR/ SUSCEPTIBILITY INTERACTION

An example of a simple failure mechanism is, for example, current breakdown in a fuse. Stressor/ susceptibility is usually performed using six steps:

Step 1. Deriving the failure mechanisms in a component.
Step 2. Deriving the stressors for the failure mechanism(s).
Step 3. Deriving the susceptibility of the failure mechanism(s).
Step 4. Deriving the stressor probability density function.
Step 5. Deriving the probability of stressor/ susceptibility interaction for the failure mechanism(s).
Step 6. Translating failure mechanisms to 'designable parameters' and optimizing the design.

The following sections will describe the individual steps in detail.

Step 1. Deriving the failure mechanisms in a component

The first step in stressor/susceptibility analysis is, normally, deriving all (potential) failure mechanisms in a component. For a fuse the most obvious (in this case even deliberate) failure mechanism is the burn-out of the fuse wire (see Figure 5).

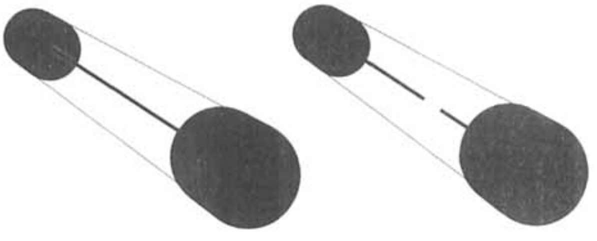

Figure 5. Failure mechanism in a fuse

Step 2. Deriving the stressors for the failure mechanism(s)

The next step in the analysis is determining what stressors can activate the failure mechanism, mentioned above. For the failure mechanism mentioned in the example the main reason for activation will be the temperature of the wire. Although it is valid to consider the wire temperature as a stressor, usually it is useful to decompose stressors down to the level of basic stressor; stressors that cannot be further decomposed completely into other basic stressors. A valid set of basic stressors for this failure mechanism could be as shown in Table II.*

Table II.

Failure mechanism	Stressors
Fuse wire burnout	Current Ambient temperature

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* Stressor sets can consist of stressors such as voltages, temperatures, etc.

* The authors are aware of the fact that the real stressor set for a fuse is much more complex. This example is intended only to show an example of stressor/susceptibility interaction.

Step 3. Deriving the susceptibility of the failure mechanism(s)

The third step in stressor/susceptibility analysis is to derive from the physical failure mechanism a susceptibility model. Such a model describes the probability of failure as a function of the mentioned stressor set.

In the case of the burn-out of the metal wire in a fuse the probability of failure depends on the probability that a hot spot in the wire reaches a temperature where the wire actually melts. Therefore it will be necessary to determine the temperature of (a hot spot in) the wire as a function of the stressor set (see Figure 6).

Assuming that this hypothetical material immediately melts at the moment a (hot-spot) temperature of 600 K is exceeded it is possible to derive a failure probability function as a function of the stressors.

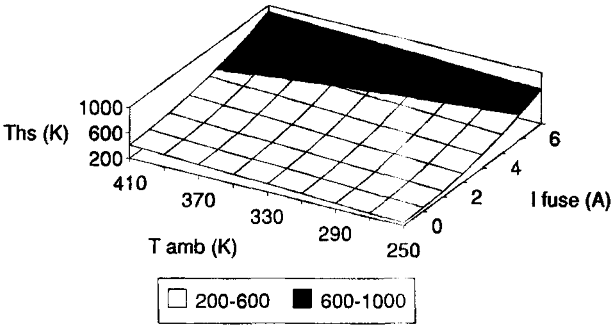

Figure 6. Fuse hot spot temperature as function of stressor set

Step 4. Deriving the stressor probability density function

The probability of failure of a certain device not only depends on the susceptibility of the failure mechanism but also on the (statistical) behaviour of the stressor set. Therefore it will be necessary to derive, based on the time dependent transient behaviour of the stressor sets so-called stressor probability density functions (see Figure 7).

A stressor probability density function models the (correlated) behaviour of a stressor set using probability density functions. The stressor probability density function models the relative probability of occurrence of a certain combination of stressors in a given interval of time.

A stressor probability density function is derived using the following steps:

1. A stressor, in the form of a time-signal, is derived from simulation (or from hardware measurements).
2. The stressor time-function is sampled in order to obtain the relative frequency of occurrence of the various stressor values.
3. From this frequency of occurrence function the discrete probability density function is derived.
4. The discrete probability density function is used to obtain an approximate continuous probability density function.

A stressor probability density function models the (correlated) behaviour of a stressor set using probability density functions. The stressor probability

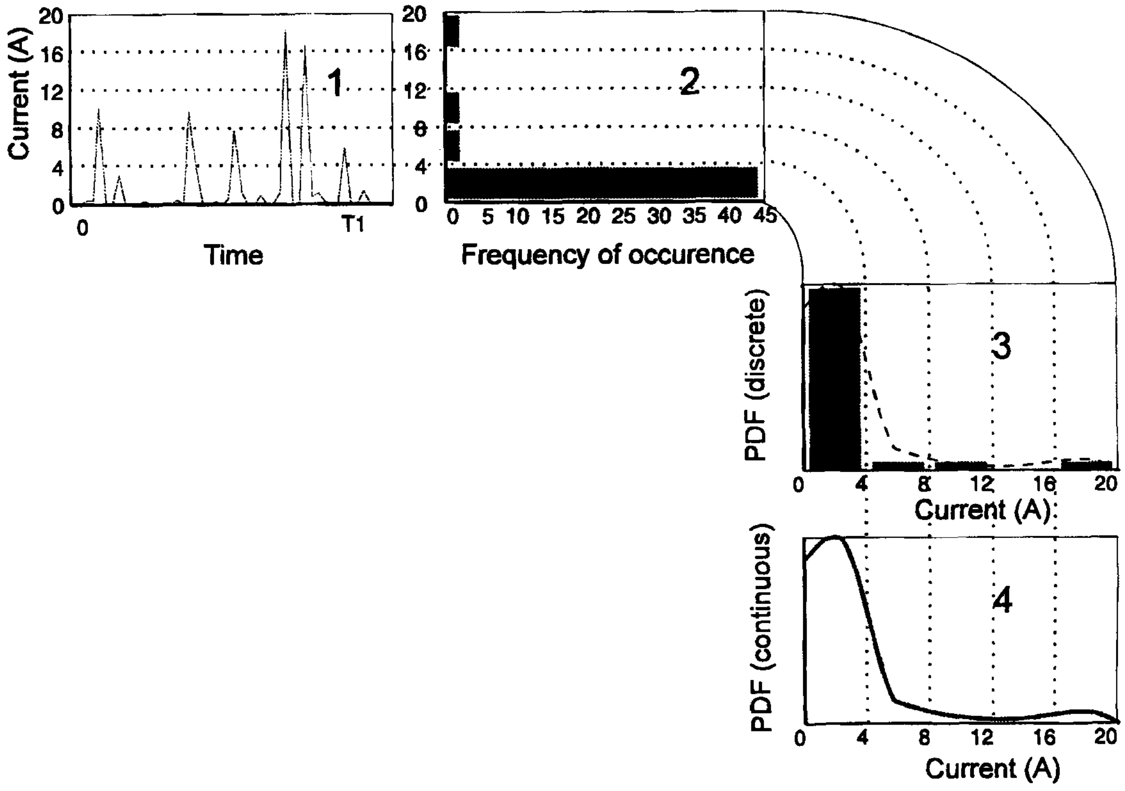

Figure 7. Translating time signals to stressor probability density functions

density function models the relative probability of occurrence of a certain combination of stressors in a given interval of time.

Step 5. Deriving the probability of stressor/susceptibility interaction for the failure mechanism(s)

In the fifth step both the stressor probability density function and the susceptibility function are used:

(a) to derive areas where interaction or overlap between the stressor probability function and the susceptibility function can occur
(b) to derive the probability of a failure occurring due to that overlap in a given interval of time (see Figure 8).

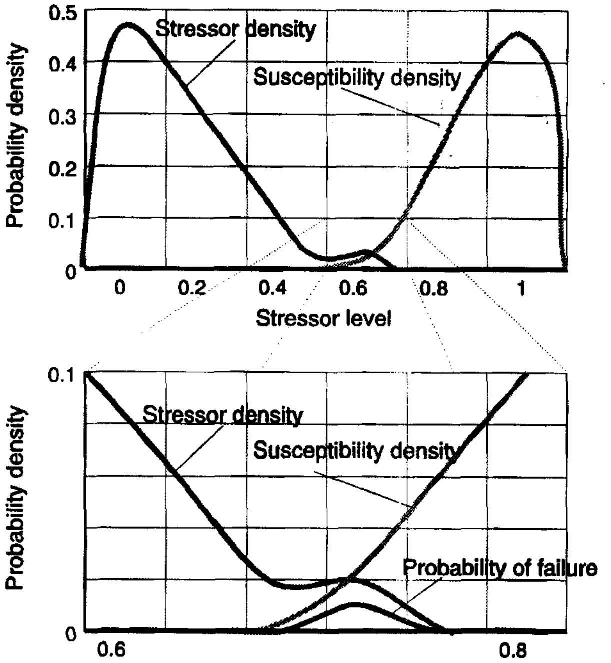

Figure 8. Stressor/susceptibility interaction

Owing to functional component tolerances the stressor set can, in many cases, show variations in a batch of circuits. In the same way, due to tolerances in material properties, a susceptibility function can show tolerances in a batch of circuits (see Figure 9).

Also both the stressor set and the susceptibility function can change with time (drift and wear-out).

These tolerances and time shifts can be used to explain the well known bath-tub curve and recently observed deviations from the bath-tub curve (roller coaster curve) (see Figure 10).[4]

Using stressor/susceptibility analysis it is possible to decompose the roller coaster curve into four different areas (see Figure 11):

1. *Early failures.* Failures at or shortly after $t = 0$: products delivered with either increased stressors (due to e.g. material tolerances or tolerances in use) or increased susceptibility (or both). Owing to the increased stressor/susceptibility interaction there is a largely increased probability of failures at or shortly after $t = 0$.
2. *Early wear-out.* (Early) failures shortly after $t = 0$: similar to 1; products delivered with either increased stressors (due to e.g. material tolerances or tolerances in use) or increased susceptibility (or both). Owing to the increased stressor/susceptibility interaction there is not the immediate danger of failure but a largely increased probability of accelerated degradation. After a certain time interval this degradation (the increasing of susceptibility due to wear-out or increasing of stressors due to drift) this may lead to a form of stressor/susceptibility interaction where there is in a certain time-interval a largely increased probability of failures (the hump in the failure rate curve).
3. *Stable system.* At the moment all subpopulations with either increased stressor/susceptibility interaction or increased degradation within a (large) batch of products have died out. At a certain moment in time there will remain a population with a fairly homogeneous stressor/susceptibility interaction. This will result in a failure probability which is to a certain extent 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 to the second part of the curve (early wear-out). In this case (long-term) degradation and (long-term) drift cause increased probability of stressor/susceptibility interaction. The population of (remaining) products is, at this interval in time quite homogeneous (see also the section on stable systems).

At present susceptibility models are available for the following failure mechanisms:

1. Instantaneous failure mechanisms:
    (a) current breakdown
    (b) power breakdown
    (c) various forms of voltage breakdown
    (d) forward bias second breakdown
    (e) reverse bias second breakdown.

2. Gradual failure mechanisms:
    (a) corrosion
    (b) electromigration
    (c) secondary diffusion.

3. Special modelling of susceptibility for stressor sets due to
    (a) electromagnetical interference
    (b) electrostatic discharge.

Further susceptibility models are at this moment

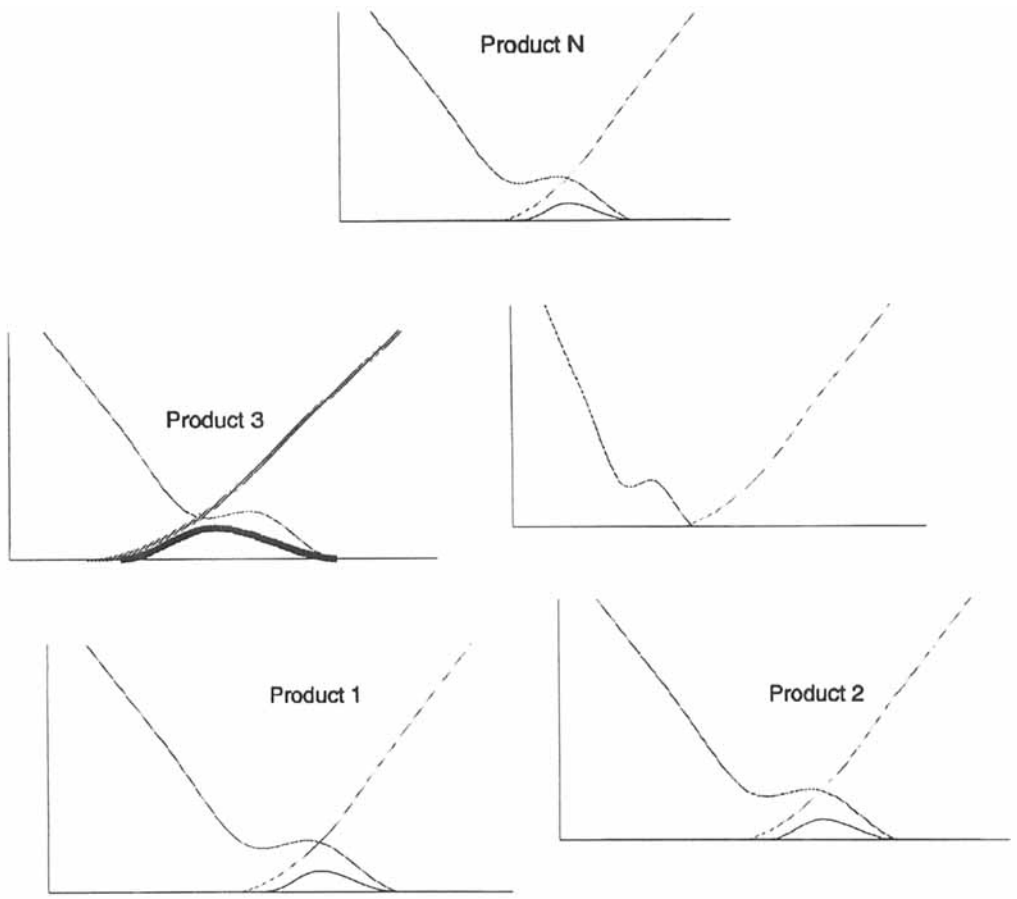

Figure 9. Tolerances in stressor/susceptibility interaction

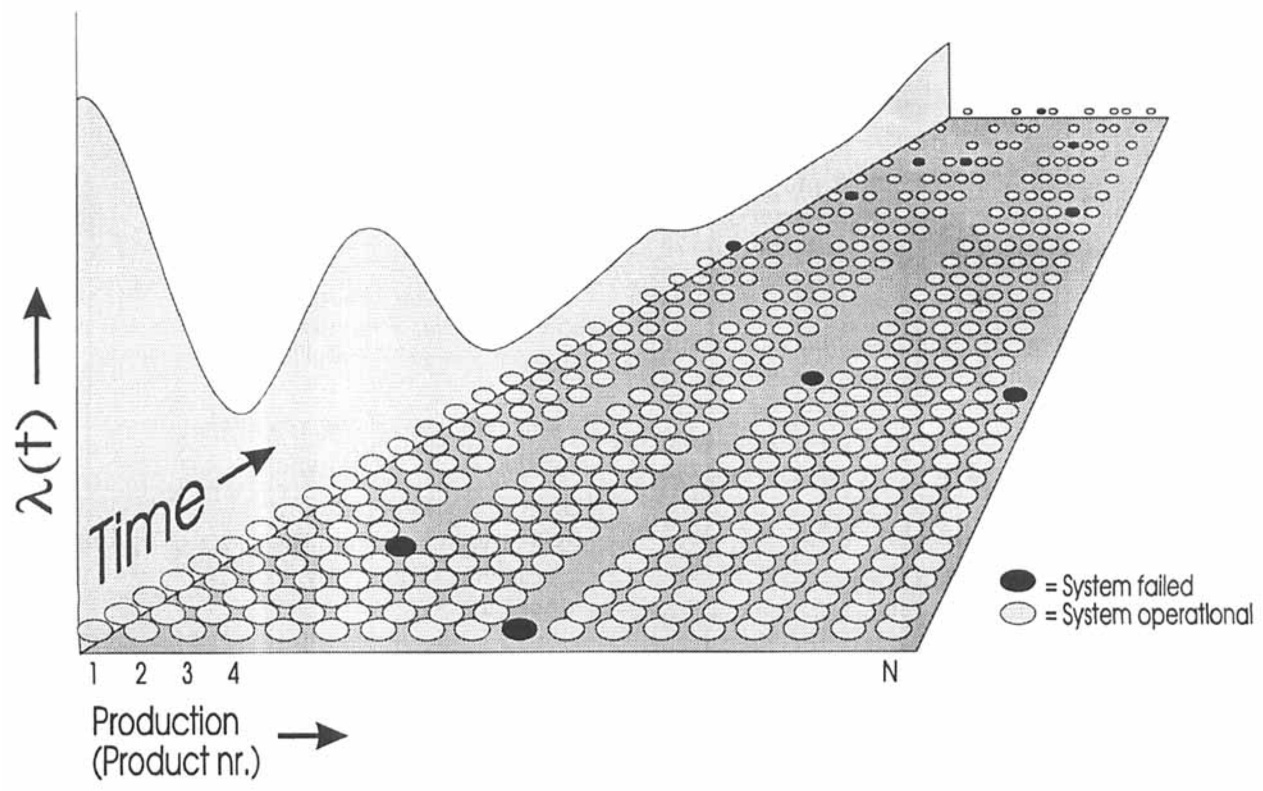

Figure 10. Roller coaster curve

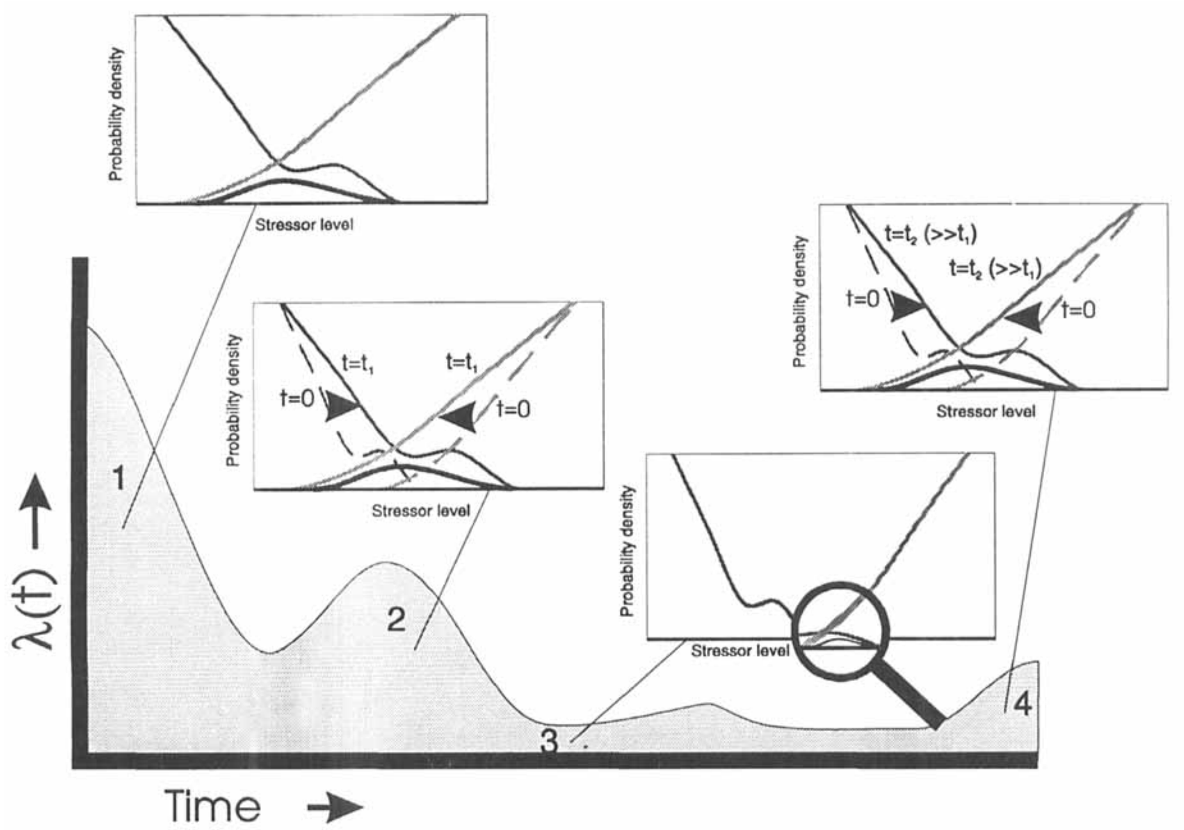

Figure 11. Relation between the roller-coaster curve and stressor-susceptibility interaction

under development in the CAIRO research project. In the CAIRO research project Twente University in Enschede (NL), Philips Consumer Electronics in Eindhoven (NL) and Imperial College in London (UK) co-operate on the development of a system for computer-aided integrated reliability optimization (CAIRO).

The primary goal of this research project is not to refine and improve basic research on failure mechanisms themselves but to bring the failure mechanisms into one common system using stressor/susceptibility models.

This is because of the fact that many designers of circuits and designers of the systems where the circuits are used will have no time available to consider every single component. The most important points for a designer will be

1. Are any failure mechanisms in a circuit or system activated?
2. If yes: with what probability?
3. With what parameters at the (circuit/system) designer level is it possible to influence/optimize the probability of activation of the failure mechanism mentioned?

The problem is that, generally speaking, every component has more than one failure mechanism; every failure mechanism and every stressor can be influenced by many designable parameters (see Figure 12).

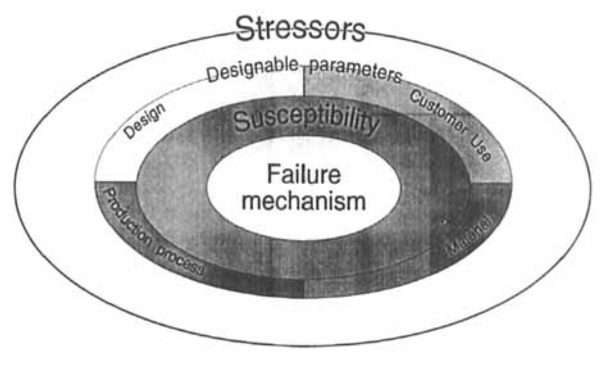

Figure 12. Need for a relation from stressor/susceptibility analysis to designable parameters at various levels

Step 6. Translating failure mechanisms to 'designable parameters' and optimizing the design

One of the methods of solving a multi-parameter problem is by means of the setting up of hardware experiments. Commonly used techniques for this purpose are

(a) Taguchi experiments[1]
(b) Shainin experiments[5]
(c) traditional design of experiments.

There is, however, a problem in analysing, for example, complex structures such as integrated circuits. At the moment actual hardware, in this case prototype silicon, is available the design is, most times, fixed to such an extent that major design changes are in many cases not practical. An alternative for hardware experiments can be found in computer simulation.

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

1. The system should be able to perform stressor/susceptibility analysis on all major failure mechanisms in electronic components on the level of major (integrated) circuits.
2. The system should derive from the mentioned analysis results components/structures/devices with increased failure probability.
3. The system should derive for the devices with increased failure probability all related parameters, at the level of the circuit design, the production processes, the material and customer use.
4. Where parameters are designable (mainly in the circuit design but in some cases also in the process design) the system should give guidelines for optimization 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 sections, 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.

Therefore for every parameter in a design the following statistical properties are determined (see Figure 13):

1. The probability density function of parameters causing activation of a failure mechanism
2. The probability density function of parameters causing no actuation of this failure mechanism

These combined probability density functions are called pass–fail diagrams[6] (see Figures 14 and 15).

COMPUTER-AIDED QUALITY AND RELIABILITY SIMULATION

At this moment a system using the mentioned methods and models is under development within the CAIRO project. The system consists of the layers shown in Table III.

Table III. Hierarchy in the CAIRO system

Optimization
Reliability simulation (Stressor/susceptibility analysis)
Tolerance simulation
Functional simulation

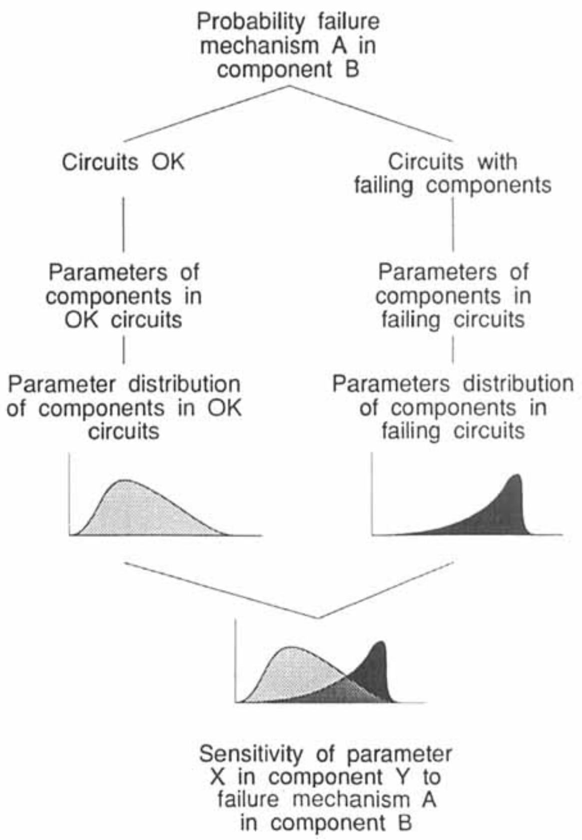

Figure 13. Deriving dominant designable parameters relating to failure mechanisms

Functional simulation

The first level of the CAIRO system consists of functional simulation. Many of the stressors relevant to the failure mechanisms mentioned earlier can be derived from electrical simulation of the network description of the circuit. For example the stressors relevant to the failure mechanisms mentioned earlier are:

(a) power dissipation
(b) voltage/electric field
(c) current/current density
(d) (stored) charge
(e) voltage slope (dV/dt)
(f) current slope (dI/dt)
(g) temperature
(h) temperature slope (dT/dt)

Of these aspects only temperature and temperature slope cannot be simulated directly. The only problem are sometimes the slope parameters dX/dt. Deriving them using numerical approximation can under some circumstances provide problems.

Another problem can be obtaining accurate functional models of the components. To derive stressors with sufficient accuracy to allow reliability prediction will sometimes require more detailed models than currently available.[4]

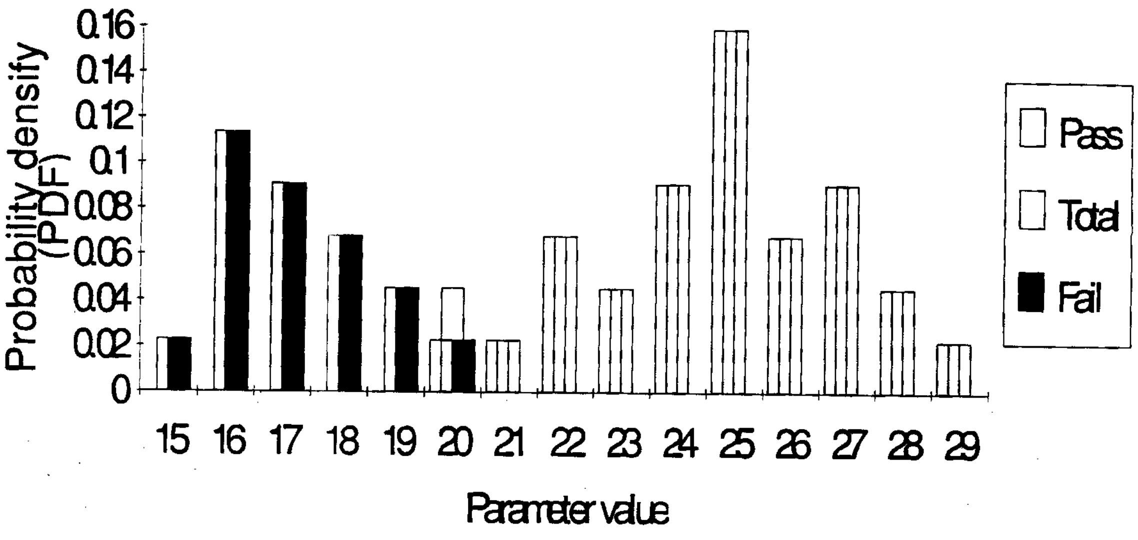

Figure 14. Pass–fail diagram showing high sensitivity

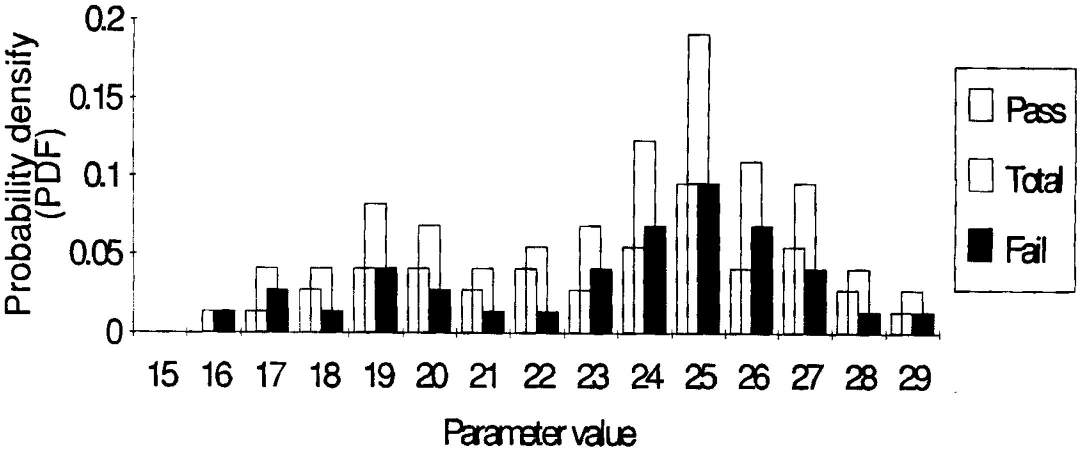

Figure 15. Pass–fail diagram showing low sensitivity

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 not only require simulation of an ideal product used under ideal user conditions but will also require analysis of the expected variability of the expected stressor susceptibility interaction.

Reliability simulation (stressor/susceptibility analysis)

This layer uses the tolerance simulation derived earlier to derive stressor sets relevant to failure mechanisms in the components used. It is important that the system has possibilities not only 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 component susceptibility parameters.

Optimization

The top layer of the CAIRO 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.

CONCLUSIONS (WHERE ARE WE NOW?)

At this moment the CAIRO system has been under development during the last five years; three years to develop the methods described in this paper and two years of actual implementation. At this moment it is possible to analyse and optimize reliability of circuits using the following failure mechanisms:

1. Instantaneous failure mechanisms
   (a) current breakdown
   (b) power breakdown
   (c) various forms of voltage breakdown
   (d) forward bias second breakdown
   (e) reverse bias second breakdown.

2. Gradual failure mechanisms
    (a) corrosion
    (b) electromigration
    (c) secondary diffusion.
3. Special modelling of susceptibility for stressor sets due to
    (a) electromagnetic interference
    (b) electrostatic discharge.

In many cases, however, the system is still in an experimental phase; see Table IV.

Table IV.

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

R: available at the research level
O: available at the operational level
− −: not available
−: generally not available
±: often available
+: in most cases available
+ +: available

Although still in an experimental phase, computer simulation has given us already in several pilot projects a very good possibility of analysing at an early phase of the development process quality and reliability aspects of integrated circuits as well as circuits using discrete components.

For the near future the research will concentrate on the translation of results of research on component failure mechanisms into susceptibility models as well as on the adaptation of the simulation system to derive the related stressor sets.

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