Reliability Engineering and Maintenance in Finnish Industry

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Key words: *Event, Cause, Consequence, Logic, Modelling, Analysis, Allocation, Simulation, Calculation, Probability, Reliability, Availability, Maintainability, Safety, Risk*

Abstract

Since 1996 eleven Finnish companies have participated in the research project which objective was to develop computer supported probabilistic based method for the development of the equipment's and systems' reliability and safety. The ideal design approach is one of those problem areas, delaying production and weaken equipments' and systems' reliability, availability and safety, are discovered and solved during the design stage.

The participating companies are both manufacturers and users in metal, energy, process and electronics industries. Their products and systems have to correspond to high safety and reliability demands. The research project was carried out by Tampere University of Technology and it was completed in February 2005. The research work was divided in three parts: modelling and analysis of causes and consequences of failures, specification and allocation of reliability, availability and maintainability requirements, simulation and calculation of reliability performance and maintenance costs. The aim of this paper is to illustrate the design methods developed in the research project and tested in numerous Finnish industry companies. Artekus Oy (www.artekus.fi) is responsible for commercializing, marketing and technical support of the developed computer software.

1. Introduction

New product liability legislation, enhanced competition, and economizing on expenditures have lent increased importance to technical considerations of reliability and maintainability in product design. A product's reliability and maintainability (R&M) are quality characteristics to which where customers attach great importance when forming an opinion of product's overall quality. It is especially important to understand that these are precisely the characteristics whose design flaws cannot be fixed during manufacturing or operation. In fact we might say that it is in the product design phase where the fundamental decisions are made to set the product's quality maximum and cost minimum. A company that has a good control of the R&M performance for its products has a considerable competitive advantage both in the case of design and manufacturing consumer products and when negotiating about availability contracts for large industrial systems.

The traditional and still dominating method for product design is focused on optimizing the technical performance of a product. However the customer expectations are today increasingly integrated as design requirements into the design process, but the reliability aspects of the product are still today very poorly attached to it. The reason for this is simple, there does not exist today an easily available and comprehensive design method or tool to integrate the reliability considerations and effects in the product deign.

The structure of the paper is as follows: In Section 2, we will introduce developed method to model and to analyze failure logic as a qualitative investigation of reliability and safety. The objective of qualitative investigation is to identify all causes and their interconnected causalities that might lead to Design Entity (=DE) not fulfilling its reliability and safety requirements. In section 3 we examine the specification and allocation of reliability, availability and maintainability (RAM) requirements set for the product and its design entities from the customer and manufacturer perspectives. In Section 4, we introduce the developed simulation and calculation methods for analysis of reliability performance and maintenance costs of a design entity.

The general term “design entity (=DE)” can stand for: say, function, system, equipment, mechanism, or any kind of part.

2. Modeling and analysis of causes and consequences of failures

The modeling and analysis of cause and consequence of failures form the foundation for quantitative investigation of design entity’s reliability, safety and risks. In this section a computer-supported method to model and analyze the reliability and safety using cause and consequence tree is represented. The developed method is a one of the main result from the research project. In reliability and safety studies the qualitative investigation includes both inductive and deductive approach for modeling and analyzing the cause and consequence logic of DE. When applying the inductive approach, we form a cause tree model to explain the causes and combinations of the causes that might lead to the TOP-event under consideration (see Figure 1). The deductive approach provides answers to generic questions such as, “what happens if…?”. More formally, we form a consequence tree model to determine all the possible consequences that might be initiated from the TOP-event (see Figure 2).

“Cause-tree” consists of causes and their interconnected causalities, which describe precisely the causes for the occurrence of a TOP-event (see Figure 1). A “cause”, which does not have any input causes, is handled as a root cause. Correspondingly, a cause with input causes is involves a “gate”. The gate logic denotes the relationship between the input causes to trigger an output. Types of gates in the method are OR, AND, k/n, Priority AND, XOR and NOT.

Notice that XOR (=Exclusive OR) gate means that *exactly* k out of n inputs has to occur, while k/n gate means at least k out of n. Priority AND means that the gate’s inputs have to occur in a specific sequence. Although the gate's inputs fulfill the gate logic, it does not necessarily mean that the gate's state will always change. In the proposed method it is possible to define this uncertainty precisely with conditional events. If the cause logic requires that there is a cause or causes, that has to be in NOT state (= complementary to failure state = success state), it is possible also to model with the method. This means that we have had to give up the concept of minimal cut sets when we analyze the modeled logic. The reason is that in the logic there can be causes which promote the occurrence of the TOP-event when they are in NOT state.

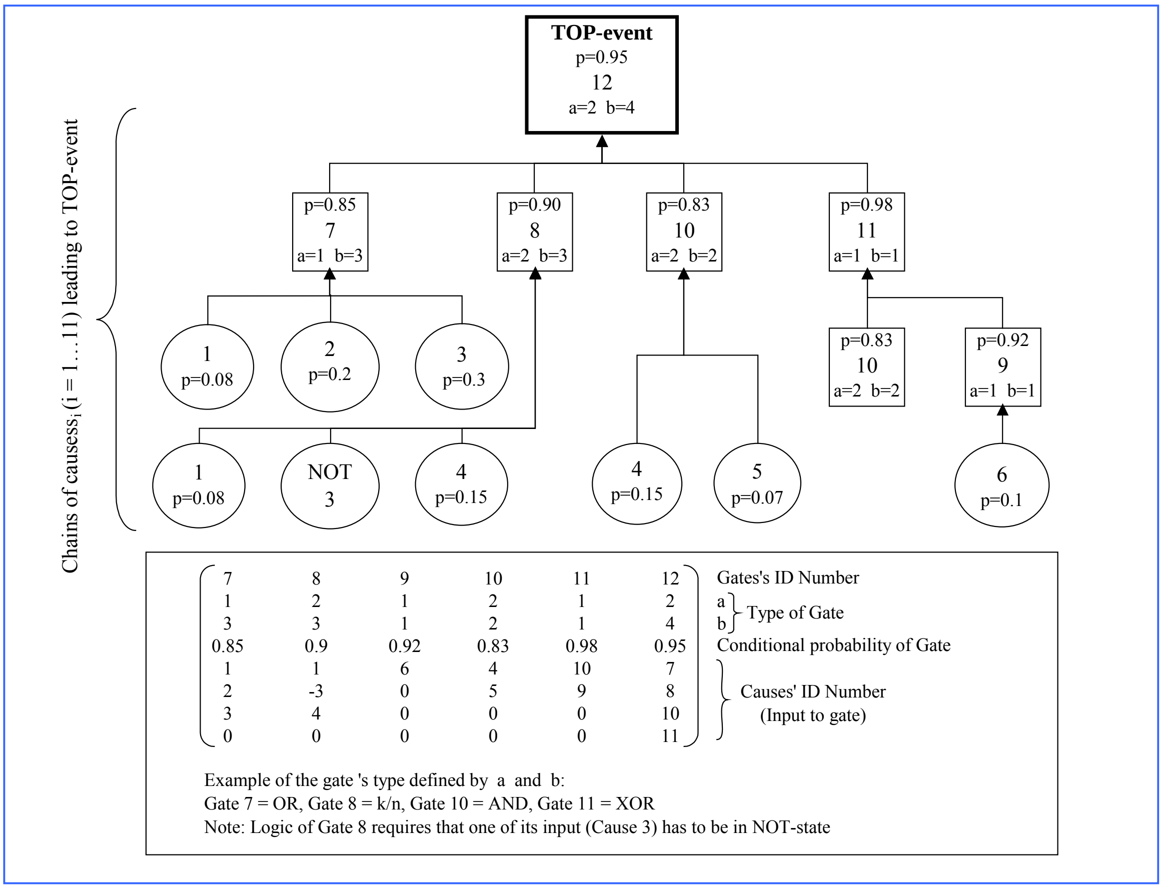

Figure 1. Principle of inductive approach to model and analyze cause logic to lead TOP

Consequence tree describes the possible chains of consequences initiated from the TOP-event under consideration (see Figure 2). Every consequence, to some extent, may cause other consequences either exclusively or independently. Conditional relations between consequences, which define their occurrence, may be modeled precisely using cause tree model. Since the cause-tree model is also used to define the occurrence of the TOP-event the developed method makes possible to describe relations and shared causes between cause and consequence structures of the TOP-event. With the developed method in the cause and consequences tree it is possible to model and analyze many different TOP-events.

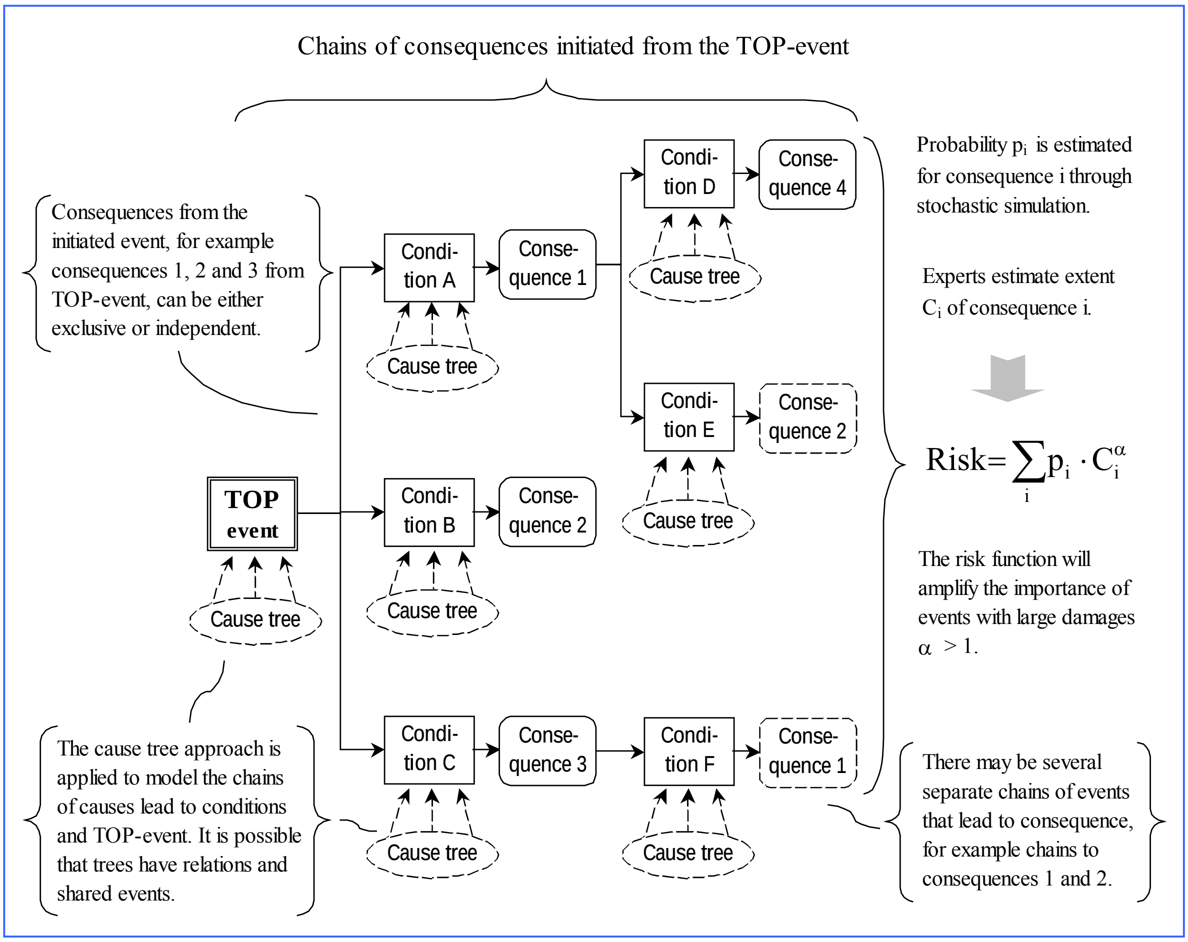

Figure 2. Principle of deductive approach to model and analyze consequences of TOP.

For the purpose, as a part of the research project we have developed Event Logic Modeling and Analysis Software (ELMAS) tool. ELMAS produces a graphical interface to model cause and consequence tree and to analyze it through stochastic simulation. Application of ELMAS to model event's cause and consequence logic related to TOP forces experts in the beginning of design stage to identify all potential events (= causes and consequences) that are associated with component hardware failures, human errors, and possible disturbances and deviations in the process and environmental conditions (see Figure 3). Cause and consequence tree method makes it possible to explain and describe precisely the relations between causes and consequences. Definition of the occurrence and extent of all possible consequences is the only way to perform a complete risk analysis for DE.

A careful choice of the top event is important for the success of the cause-consequence analysis. In the risk analysis applications, the initiating event is typically a system failure. If the top event is too general, the analysis becomes unmanageable, and if it is too specific, the analysis does not provide a sufficiently broad view of the system. The scope of modeling and analysis of cause and consequence of failures is affected not only by the size of estimated risks, but also by available time, personnel's reliability and safety technical know-how, financial resources, and the importance of the project among its interest groups.

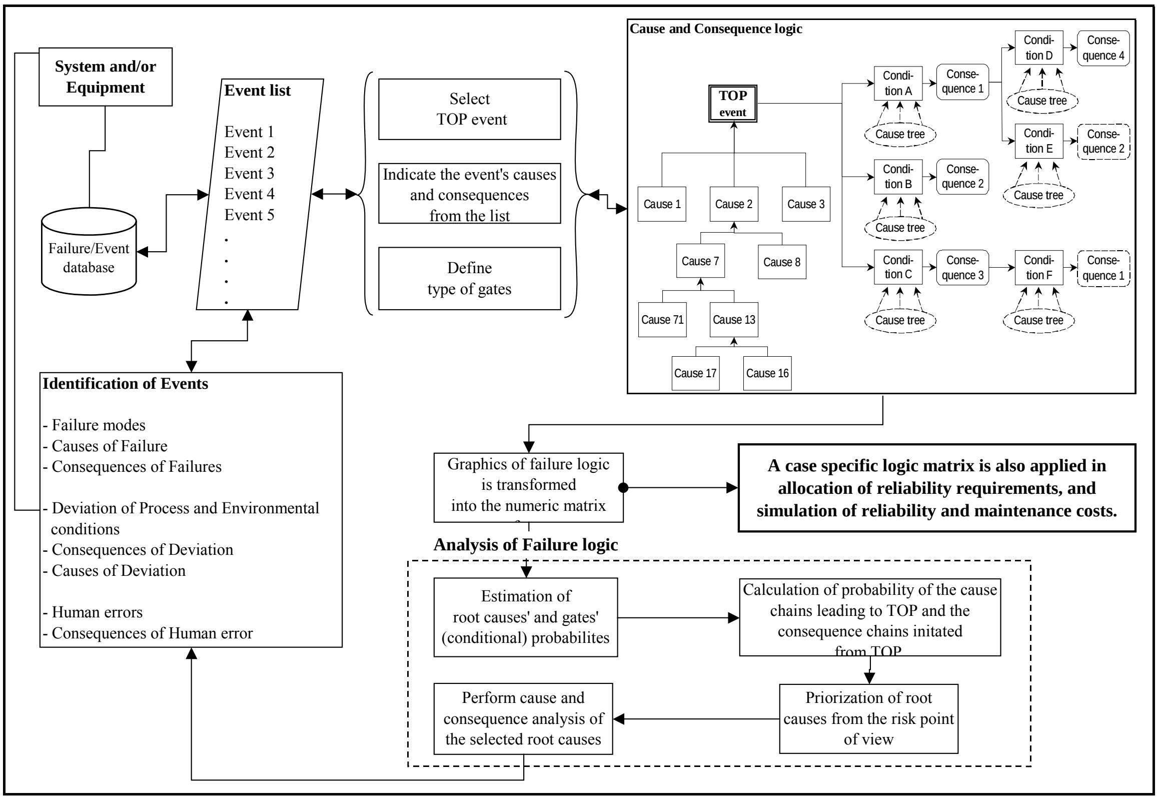

Figure 3. Principle for modeling and analyzing the cause-consequence logic with ELMAS

After the TOP event is selected, experts examine the generated event list one by one and indicate the event’s cause and consequence connections in the other events. Based on the expert’s decisions, ELMAS draws the logic diagram on the screen. As in real life the same cause can occur in many places in the logic. On the computer screen the expert can drag and drop the events in to the right position based on his/her best understanding of the logic. If the event is moved so that it leads to a loop in the tree, ELMAS gives a warning and rejects the choice. After events’ causes and consequences are determined, the type of gates is defined (see Figure 3). For the analysis of causes and consequences of failures, the estimation of all root causes and gate probabilities is performed. In this task many different types of expert judgment methods are integrated into ELMAS.

In ELMAS the numeric logic matrix that is transformed from the graphic is analyzed through stochastic simulation. Results from the analysis help researchers to identify the most probable causes and chains of causes both leading to the TOP-event, and the most significant consequences and chains of consequences initiated from it. According to the extent of consequences, causes can be ranked from the risk point of view (see Figure 2). After ranking the causes, a more detailed root cause analysis can be performed by applying FMEA-method, which is integrated into ELMAS. A case specific logic matrix is also used in allocation of reliability requirements, and simulation of reliability and maintenance costs see Figure 3. This is discussed in the following two chapters.

3. Specification and allocation of RAM requirements

The knowledge level in the industry for definition and allocation of reliability, availability and maintainability (RAM) requirements varies greatly. There is often inconsistency in the setting of requirements; either the customer requirements are not understood or they are ignored unimportant. Also customers' requirements for reliability and availability may often be contradictory. Problems often arise from insufficient knowledge of customer requirements or ignorance about how a product will behave in changing conditions. Changes in environmental conditions and the way in which the product is operated and maintained have an enormous impact on its RAM. Nowadays, the customer expectations are increasingly integrated into the design process as design requirements. However, the RAM aspects of the product are still today very poorly integrated into the design process.

In the design methods used today it is very much the design engineer that is responsible for the product reliability. How well this is in balance with the customer expectations depends on how well the designer knows the end user and how well the RAM requirements have been specified. Typically problems arise when either 1) such a reliability performance is promised to the customer that cannot be achieved or 2) achieving the promised performance becomes very expensive for the company. The design method developed in this research is focusing on finding solutions and tools to overcome these problems.

In this section a computer-supported method to specify RAM requirements for a product and then allocating into the product's design entities is represented. First the critical customer data, which influences product reliability and availability, is defined. In our proposed method, the customer (and/or the manufacturer) requirements relating to failure tendency can be stated in terms of the age of the product. They can involve number of failures, time between failures, reliability and availability as a function of age, or data concerning first failure. Our method is flexible from this point of view, since it is always closely connected to failure tendency defined by I(t), with the expected number of failures over the age interval $(t_1, t_2]$ is given by the difference $I(t_2) - I(t_1)$. Data concerning the number of failures corresponds directly to I(t), the failure rate (λ) or MTTF to I'(t) $(\equiv dI(t)/dt)$, reliability data to $R_L(t) = e^{I(L)-I(L+t)}$, and availability data to $A(t) = (1 + MTTR \cdot I'(t))^{-1}$. Requirements related to product's repair time could involve the mean time to repair (MTTR), minimum (0%) and maximum (with corresponding quantile %) repair time, and standard deviation.

From the customer data the distributions for the product reliability, availability and repair time are derived, and the product specific RAM requirements can be specified (see Figure 4). The proposed method can deal with quite different types of requirements for the product, leading to quite different failure tendencies. For instance, from both the customer's and the manufacturer's perspective, there is possibility to accept a different failure tendencies during the warranty period and post warranty.

Running time (t_d)		39420 hours	
$I(t_d)$	61.1	Repair time	399
$I(t_b=8760)$	22.3	$I(2\cdot t_b)-I(t_b)$	4.7
$A(0 - t_b)$	0.9800	$A(t_b - t_d)$	0.9878
$A(0)$	0.9600	$A(2\cdot t_b)$	0.9950
$R(0\ldots168)$	0.4242	$R(t_b..t_b+168)$	0.8460
MTTFF	202	MTTF	791
MTTR	8.0	TTR_{95}	25.0

RAM = Reliability, Availability, Maintainability
t_b = age at the end of warranty period
t_d = age at the end of useful life period
I(t) = Expected number of failures during the 0…t
Reliability = $R(t_1\ldots t_2) = e^{I(t1)-I(t2)}$
MTTFF = Mean time to first failure
MTTF = Mean time to failure
A(0 - t) = Average availability
MTTR = mean time to repair
TTR95 = maximun repair time (95 %)

Figure 4. Example of the product's RAM requirements specified from the customer data

Requirements allocation is carried out based on a cause tree approach (section 2) that characterizes the design entities and their causal interrelations that lead to the product's (=TOP) failure see Figure 5. In the allocation the failure tendency function I, and the cumulative probability distribution for repair time G, modeled for the TOP, will be transferred to corresponding functions for the input DEs. The portions are defined by the dependability allocation principles:

$$I_i(t) = \alpha \cdot w_i \cdot I(t) \qquad G_i(x) = G(x)^{\beta \cdot z_i}$$

In the allocation of failure tendency (I), the allocation coefficient w is composed of the importance and complexity coefficients x and y. The importance coefficient takes into account customer's perspective and complexity coefficient represent the technical standpoint. The aim is that the more important an entity is (x high) the less it is allowed to fail, and the more complex it is (y high) the more it is allowed to fail. A reasonable, simple way to implement these effects is the following:

$$w_i = \frac{\dfrac{y_i}{(x_i)^\varepsilon}}{\sum_i \dfrac{y_i}{(x_i)^\varepsilon}} \qquad (\varepsilon \geq 0)$$

Heuristically speaking, the greater consequences a failure of a DE leads to, the more important this DE will be from the customer's point of view. Accordingly, the more rarely this DE is allowed to fail, i.e., a high reliability should be allocated to it. And the more complex a DE is to implement technically, the more probable that it will cause the product's failure, and hence the lower the reliability that should be allocated to it.

The exponent ε = 0 is quite often used, and it means that consequences of failure will not be considered at all. Another choice, ε = 1, gives importance too strong weight from a practical point of view in some applications. Based on our experience the choice ε = 0.5 offers a reasonable balanced solution by default. As a consequence of the resulting allocation of reliability (failure tendency), one may, for example, arrive at such a strict requirement for a DE's reliability that it becomes technically and economically impossible to attain. This may be the case with a DE whose importance to the customer is greater than for other DEs. In our model, the DE's failure tendency (I_i) and/or repair time ($MTTR_i$) can be locked in advance, when the rest of the gate's failure tendency and repair time will be allocated to the other DEs of the gate according to the allocation method.

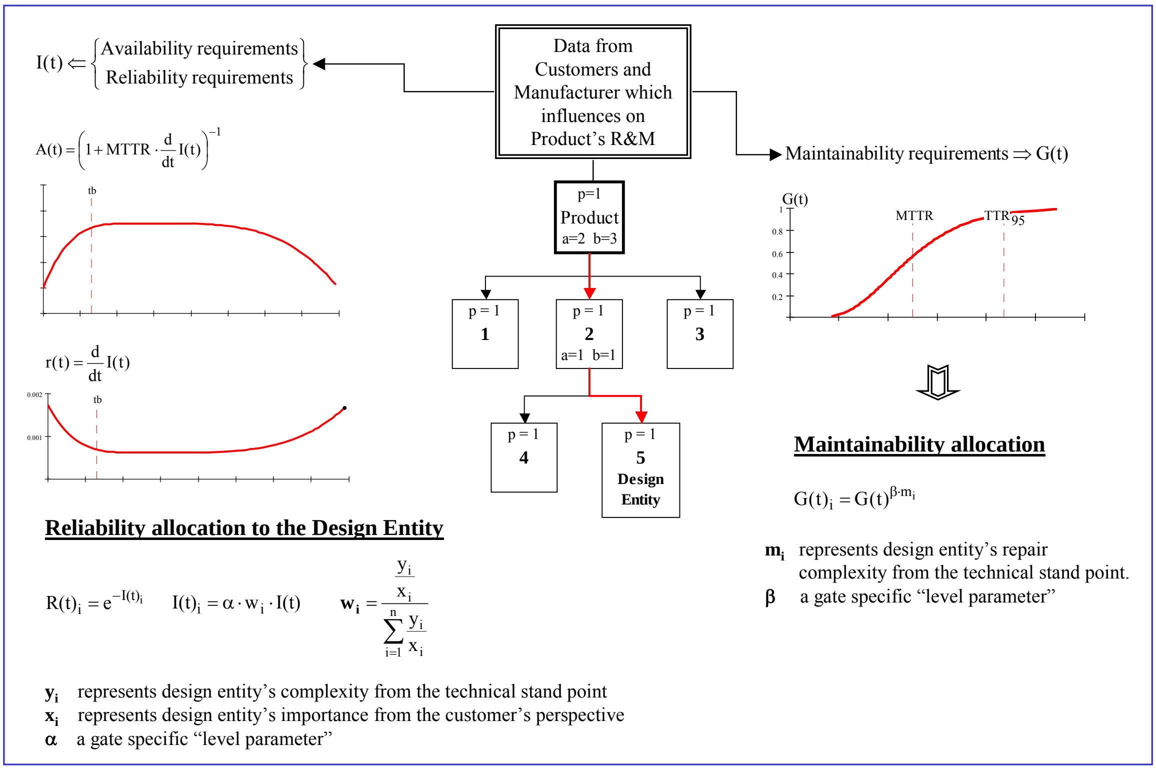

Figure 5. Principle of the RAM allocation method developed in the research project

Importance and complexity can in general be both case and DE (gate) specific. In our model, we need only case specificity, that is, we use the same factors for all gates. These are importance factors:

D = property damage
E = environmental damage
F = human damage
G = business damage

and complexity factors:

A = number of "parts"
B = level of human activities
C = level of "state-of-the-art"

The importance factors D, E, F, G represent possible damage types caused by failure. The complexity factors A, B, C reflect the implementation of a product's technology. For example, the "state-of-the-art" factor C takes into consideration the present engineering progress in relevant fields, related to the design and development phase of the product. An aim in selecting the complexity factors has been to avoid bias and inconsistency. The designer should assign relative weights (positive real numbers) to the selected importance factors according to the probabilities with which different types of damage can occur. The corresponding weights (positive real numbers) for the complexity factors again are estimates of how much complexity each factor represents. The assessment of the weights is in practice a very intuitive process, during which experience-based simple pair or other comparisons can be very helpful. The choice of weights can, of course, be done separately for each gate to be allocated.

The repair time allocation coefficients z_i describe directly and proportionally the repair time for the DEs belonging to the gate. The greater the z-coefficient of a DE the longer the repair time that will be allocated to it.

Numerical experience shows that the allocation principle is applicable for arbitrary k/n-gates by appropriate choice of the level parameters α and β. The values of the level parameters are to be set by the designer to meet TOP-requirements using a "trial and error" method. The following general instructions for the choice can be given. In case of an OR-gate, the natural first attempt would be $\alpha = 1$ and $\beta >> 1$. The value $\beta = 1$ again corresponds approximately to an AND-gate, where all input DEs are being repaired simultaneously and the repair is defined to be finished when all input DEs are finished. Thus, choosing initial values for α and β, we define tentative probability distributions of the input DEs of the gate. These distributions are then tested by simulation. In our simulation procedure, in addition to the fault logic, there are other features that affect reliability and availability. One of these is the operation strategy based on extra interrelations between TOP and DEs. We define the following three DE specific strategies:

The DE cannot be repaired if TOP is running:	$a = 1$, otherwise $a = 0$
The DE is not running if TOP is not running:	$b = 1$, otherwise $b = 0$
TOP will not be started if the DE is in failed state:	$c = 1$, otherwise $c = 0$

The allocation model for failure tendency uses age as the basic variable, but the age of a DE does not increase if the DE is not running. If we know advance that the DE's running time does not accumulate at the same rate as a gate's running time or so that its total running time is less than gate's running time, then our model takes thus into account by modeling DE's running time as a function of a gate's running time. So to have consistency with the mathematical model, the simulation must observe when a DE or TOP is not running, or can not be started although it is logically non-failed. The operation strategies are, in principle, defined independently from the fault logic, but they will of course be applied only if the fault logic is allowing it.

The simulation generates failure moments and repair times for the input DEs, considers fault logic and operation strategies, and continuously documents the age and state of the DEs and the TOP. Note especially that the simulation is, as always, done up to the TOP and not to the gate under allocation. Consequently, the simulation results are always compared to the original requirements for TOP. This way ultimate flexibility will be achieved. The final values of the level parameters α, β ensure that the requirements are met more effectively than if the simulation stopped with the gate under consideration. This also implies that the distributions allocated earlier from above to the specific gate itself become unnecessary and irrelevant as soon as distributions have been allocated to its input DEs.

For the purpose, as a part of the research project we have developed a software for the reliability, availability and repair time allocation (RAMalloc). The developed software forces the designer, early in the design stage, to work out which customer and manufacturer needs should be used to determine the product's quantitative RAM goals. As requirements are being defined for the product, there is from both the customer's and the manufacturer's perspective an opportunity to accept a different probability of failure during the burn-in phase than after it. With the software RAM requirements can be allocated to the functions, systems, mechanisms and parts as the design work proceeds and design solutions are known.

The input data necessary for the specification of importance and complexity coefficients has been selected so that in the design of a new product they can be inferred unambiguously, at the same time avoiding inconsistencies in the implementation of pair comparisons. In the specification of the importance coefficient used in the allocation of requirements, the designer is forced to become familiar with the overall process of which the product forms a part, and to assess the probable consequences, both in terms of safety and in terms of RAM, that might arise from the product's failure. In the specification of complexity coefficients the designer must familiarize himself or herself at an early stage of design, and in accordance with the Product Liability Act, with the factors that will most likely affect the product's failure. The allocation of repair time is determined by the complexity of repair, not by how often a probable need for repair appears.

The effect of RAM requirements defined by the customer and manufacturer on the known technical solution of a product can be demonstrated with the software. This connection is important in order to avoid promising something that cannot be achieved or the achievement is very expensive. The software can be applied both to tailor-made business-to-business products and to ordinary consumer goods.

The concept of allocating RAM to functional entities enables the design team to elude the problem of being bound to any one particular technical solution. This helps in maintaining an accurate allocation model, since changing the technical solution does not necessarily require a change in the allocation model.

RAM requirements allocated to DEs were directly applied to inquiry specifications. Calls for bids contained brief explanations to suppliers how they had settled upon the requirements set. As a result the suppliers all produced the requisite data, along with substantiation, which had never earlier been provided.

4. Analysis of DE's reliability performance and maintenance costs

In our research project the method to design product's reliability and availability is developed, see Figure 7. Both qualitative and quantitative methods should be used in product's RAM design process. In Section 2, we have taken a look at the method to model and analyze failure logic as a qualitative investigation of reliability and safety. In section 3 we introduced the method to define RAM requirements to the product's DE. In this section we will look at the main part of the developed method to assess that a proposed design solution will fulfill the numeric requirements set for its RAM.

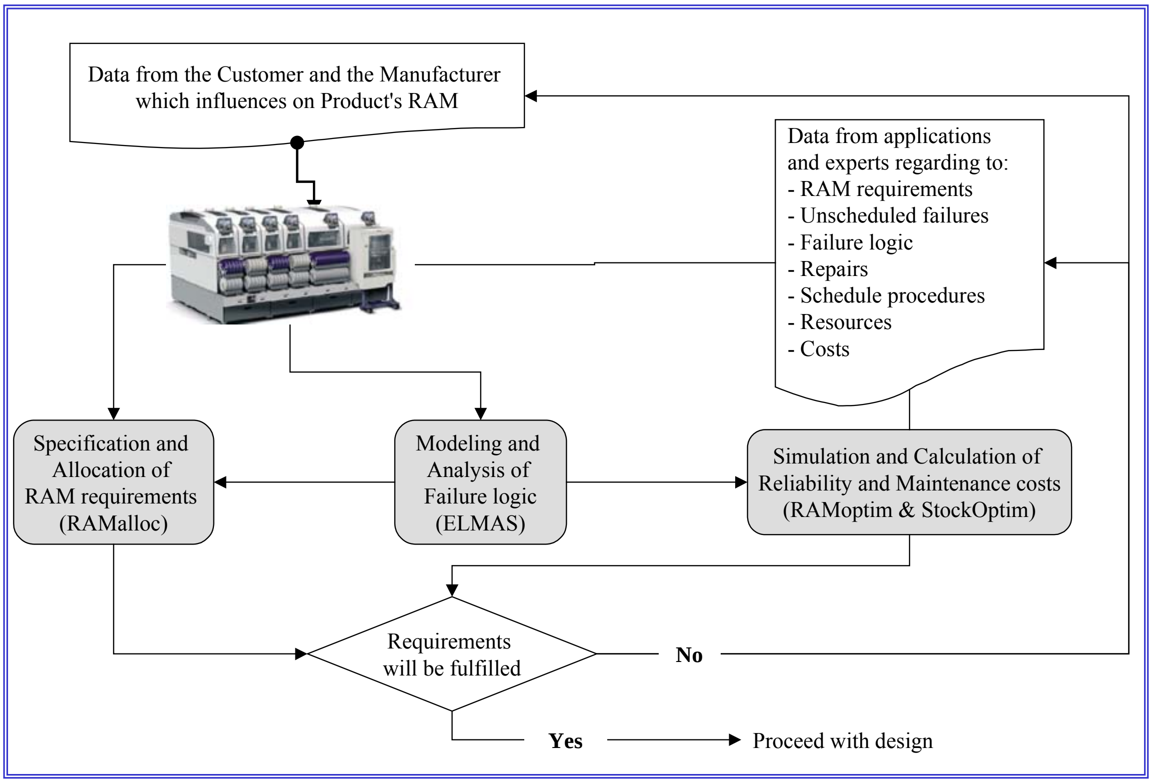

Figure 7. Probabilistic approach to define RAM requirements to the product's DE and to assess that a proposed design solution will fulfill the numeric requirements set for its RAM.

The likelihood that a design solution will fulfill the numeric requirements set for its RAM can be assessed in theory using three different sources of data: applications, generic data banks, and expert judgments, see Figure 8. If the required RAM has not been achieved, the expert must go back to the drawing table to consider solutions in which requirements might be achieved. Data from applications consist of data compiled statistically from the operation and maintenance of the manufacturer's own similar products. Generic data consist of data available in general sources on operational reliability. Expert judgment data consist of the assessment formed by the team of experts of the DE's RAM based on design documents. The source data required for simulation have been selected in a way that it would be as easily and reliably assessed by designers as possible.

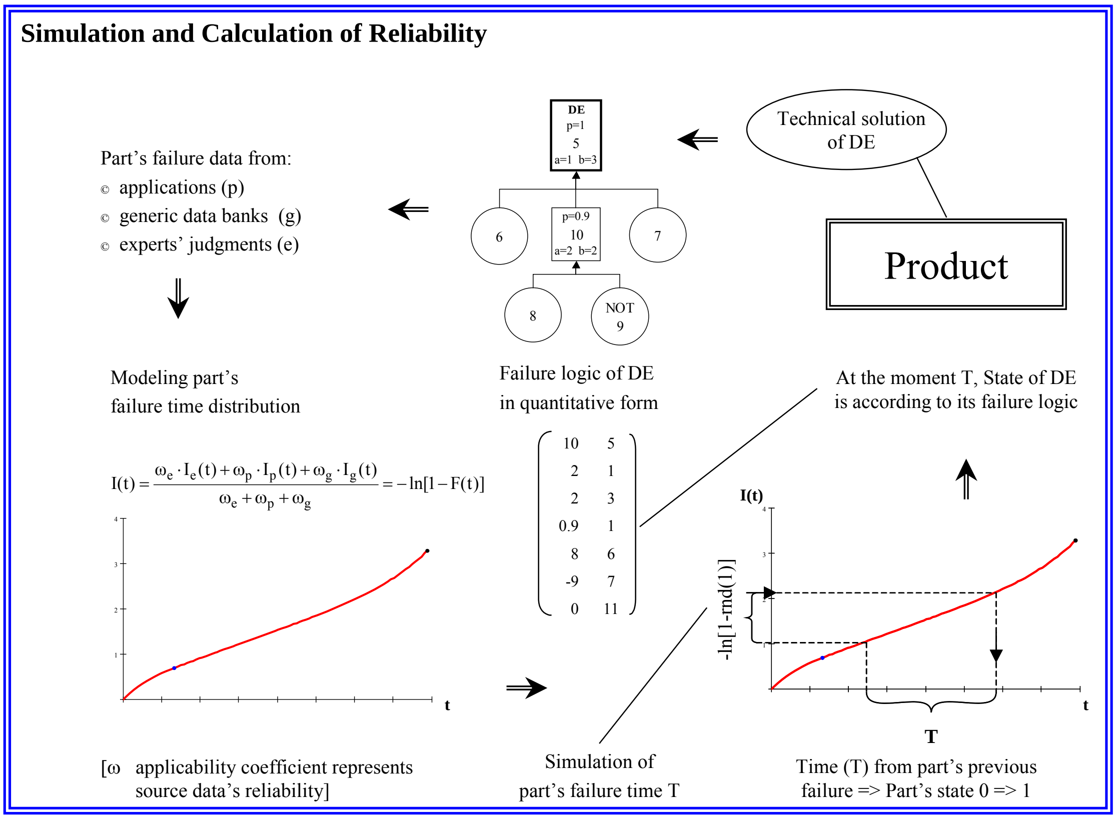

Figure 8. A basic idea to refine input data from the source data available for simulating the reliability of proposed design solution

When using the method, the designer has a possibility to determine, already in the early stage of the design, what level of reliability can be attained using the design draft selected. In addition, the method may be used to import expertise into the design process from areas that powerfully affect the success of that process, namely the manufacturing, testing, operation, and maintenance of the product.

During the last three years one of the main subject in our research project has been to develop a computer supported methods to quantify the effect of preventive maintenance on a part's failure tendency. With the help of this method, the effects of maintenance actions and maintenance interval on failure tendency can be quantified in different phases of a product's life cycle, see Figure 9. Another main focus in our research project during the last years has been to develop a computer supported method to optimize availability and maintenance resources and spare parts, see Figure 10. Condition monitoring resources are included in preventive maintenance resources as well.

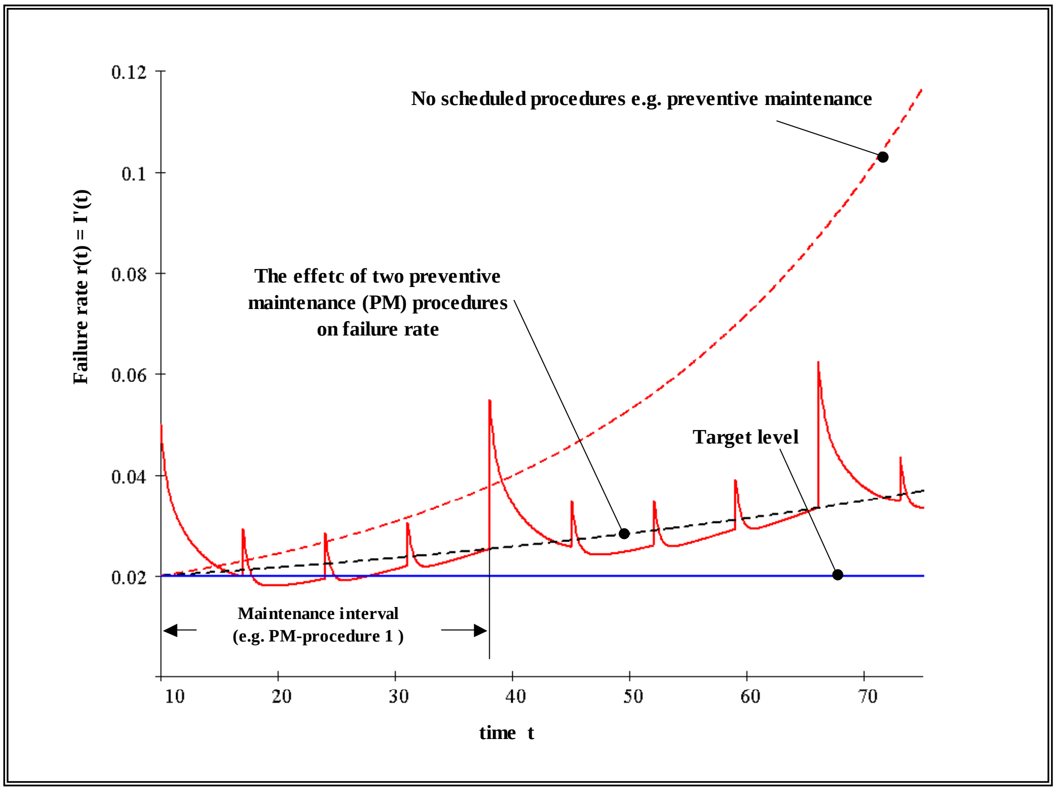

Figure 9. An example of preventive maintenance's effect on part's failure tendency.

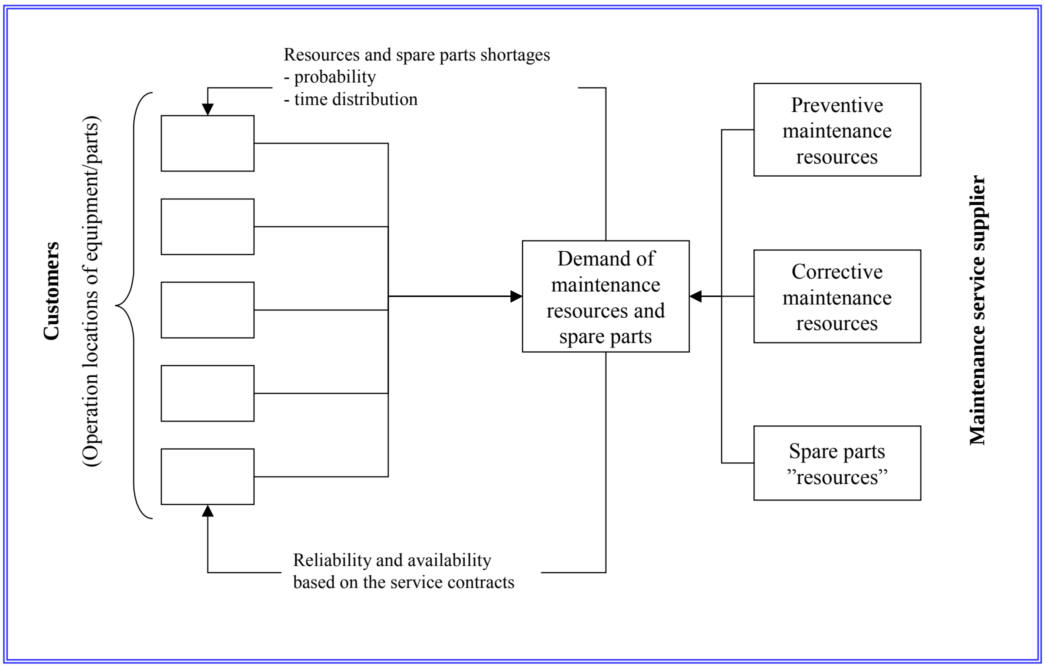

Figure 10. Equipment reliability and availability versus demanded maintenance resources and spare parts.

The optimization of spare part stock to meet the technical and economical requirements set to the service supplier is a challenging and multiphase task. The most important variables of optimizing a spare part stock are the part's order point, amount of parts to be ordered, part's failure tendency (=> part's consumptions) and delivery time, see Figure 10. The structure of the simulation and calculation software (StockOptim) developed in our research project is illustrated in Figure 11.

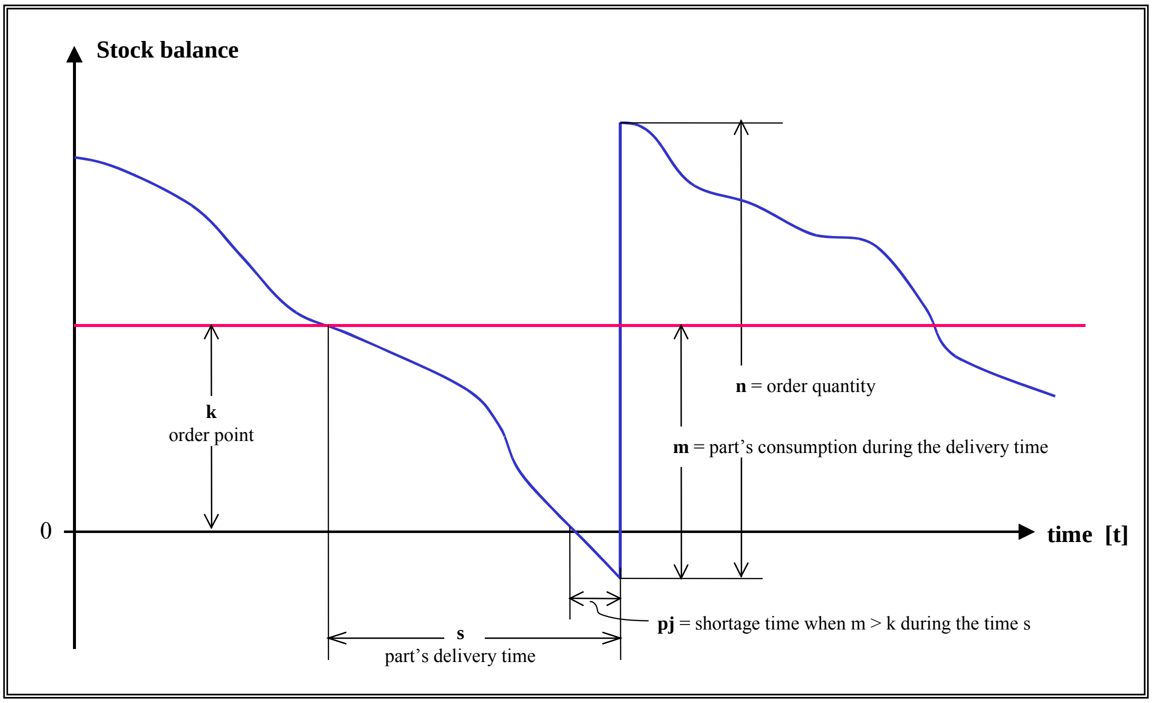

Figure 10. The main variables effecting stock balance and part's shortages

Selecting the best solution from a RAM standpoint requires the use of various design techniques and models in comparing the different technical solutions and maintenance strategies of the product and systems. The structure of the simulation and calculation software (RAMoptim) developed in our research project for reliability and maintenance cost optimization is illustrated in Figure 12.

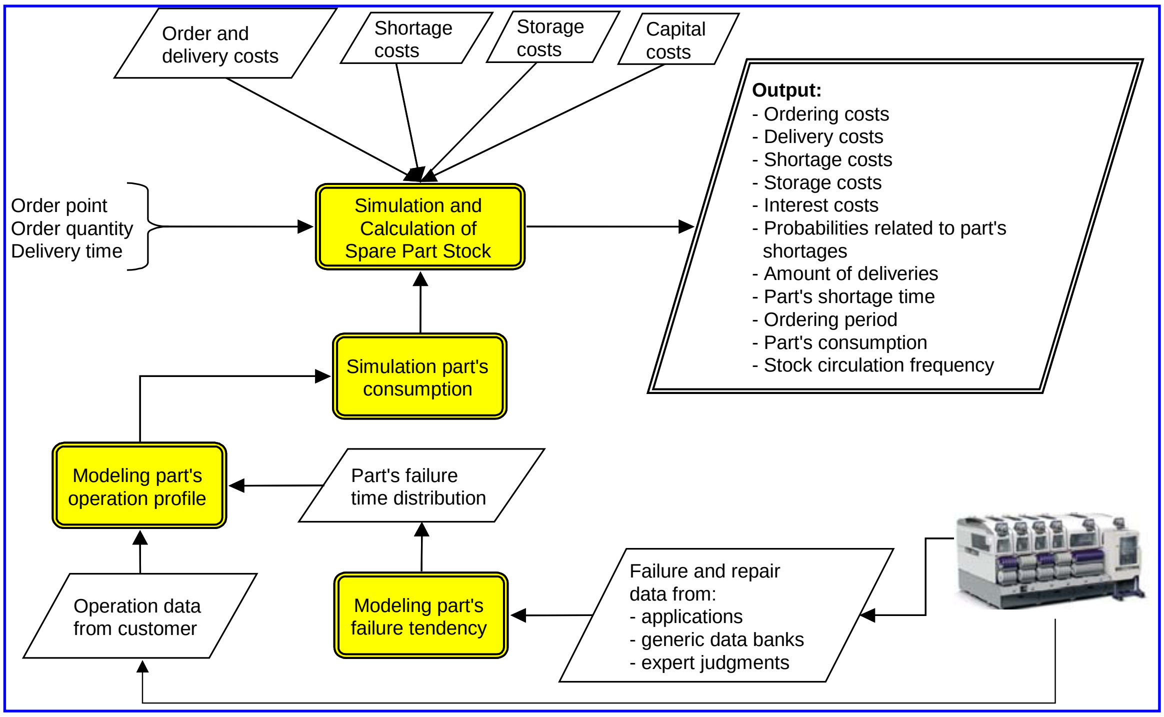

Figure 11. Structure of simulation and calculation software (StockOptim) developed for optimization equipment reliability and spare parts costs

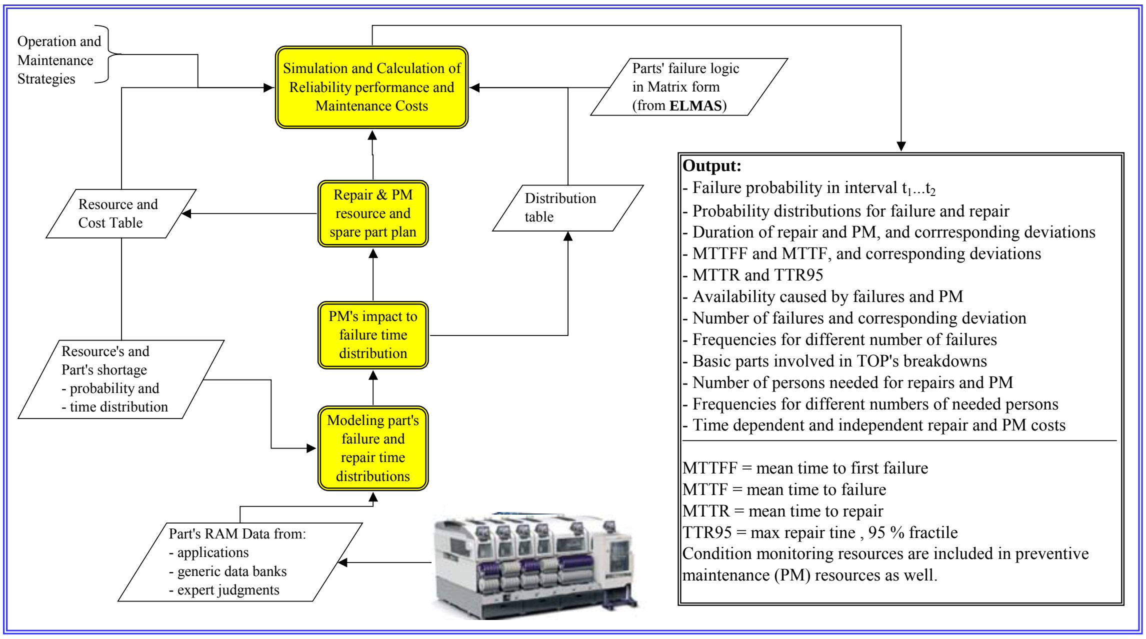

Figure 12. Structure of simulation and calculation software (RAMoptim) developed for a reliability and maintenance costs optimization.

The applicability of the developed methods and software has been tested in numerous Finnish industry companies. Most of the participating companies have started to apply the proposed method and software for developing reliability and maintenance services for their systems and products. Based on the experience and the help of the methods, it is possible to find out those problem areas in the design stage, which can delay product development or reduce product's safety and RAM. Based on experience and with help of the software, the effects of design solutions and maintenance strategies on product's reliability performance and maintenance costs can be estimated. The application of the developed methods into product design and development process requires increased RAM-technical know-how of engineers. The companies should also develop RAM related data collection methods in order to serve product design and development process.

Future research activities

At the moment we have ongoing a research project which objective is to develop a design module that brings the reliability consideration and the economical and business expectations into the process of product design, see Figure 13.

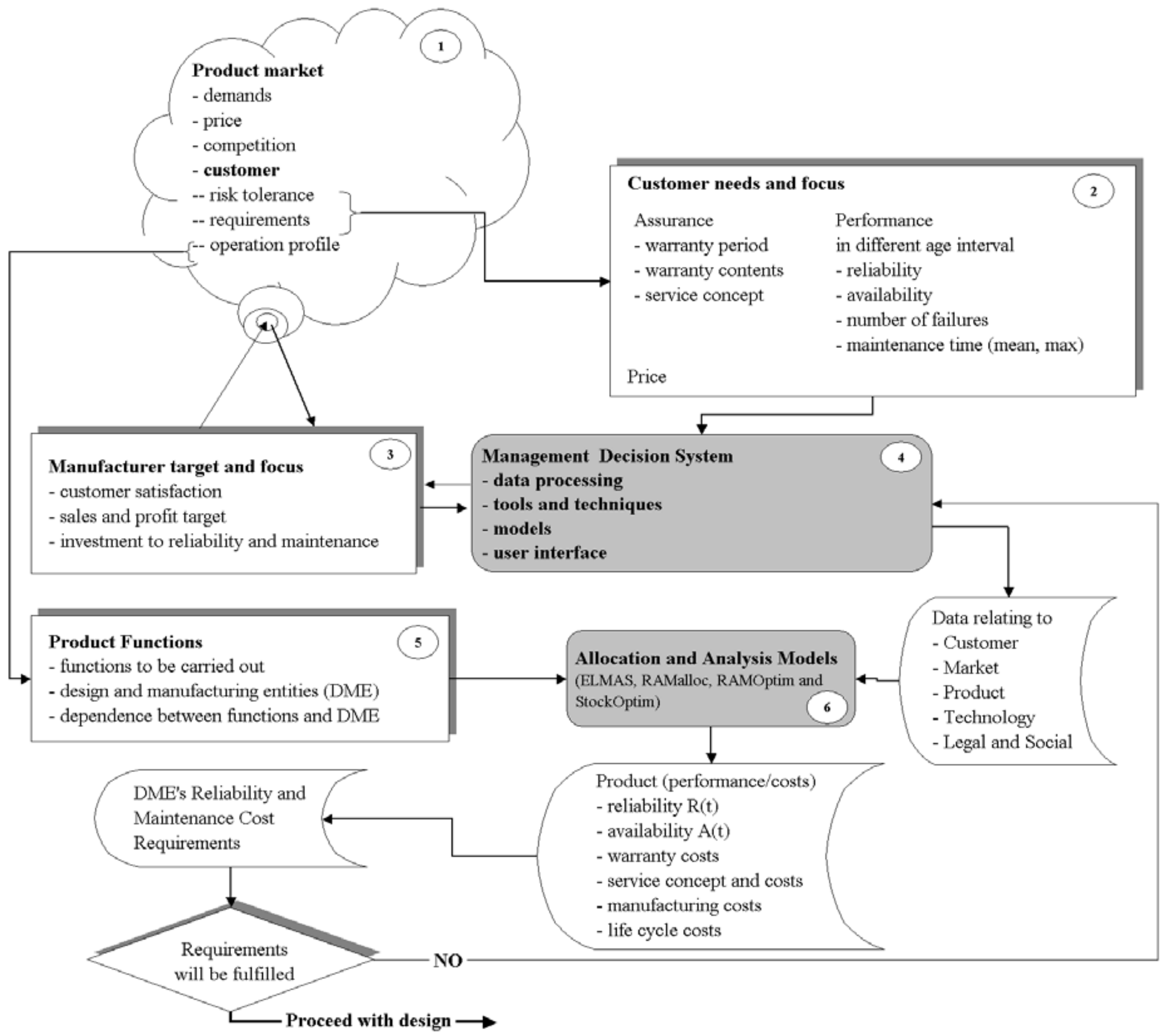

Figure 13. Concept to link the customer needs, the manufacturer's business targets and the product reliability performance

The concept consists of a holistic business-reliability structure, which includes elements such as: a tool for making reliability facts visible for business level decisions and a tool for including the customer view into the reliability of the product. This can be integrated into the reliability design and analysis modules for product design developed recently by Tampere University of Technology. This makes it possible to simulate in detail level, which are the specific customer product reliability requirements, and to determine what influence the reliability performance has on the customer satisfaction. In addition the method enables to assure at different phases of the design process that the promised reliability performance can be delivered to the customer in accordance with the business expectations of the top management. Therefore the method enables product reliability facts to be taken into account at the business decision level.

Tampere University of Technology, VTT Industrial Systems and University of Queensland, Australian will carry out the project. The project will end in April 2007. One basis for this research work is the work on reliability design and analysis carried out by Tampere University of Technology during the last nine years, introduced in this paper. Professor D.N.P. Murthy from the University of Queensland (UQ) in Australia is one of the leading experts and scientists in reliability engineering in the world. He has published a great number of scientific papers, books and carried out industrial consultancy in many countries in different parts of the world. He has recently developed together with Ostreas and Rausand from Norwegian University of Science and Technology in Trondheim a new method called "Reliability Performance and Specifications in New Product Development". The novel feature of this is focusing on the front end in the product development process. This new approach as well as the large experience of professor Murthy will be benefited in the research project.

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Biographies

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