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Continuous CAD-integrated Reliability Evaluation Throughout the Design Process

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Abstract

With the integration of reliability evaluation and calculation into computer-aided design (CAD), the designing engineer has the opportunity to determine the lifetime while developing a new product.

Instead of calculating the lifetime of the product at the end of the development process, with this feature, it is possible to evaluate the lifetime from the beginning of the development process. Furthermore, the design process becomes interactive with reliability methods, which can be used in the habitual surrounding, i.e. the surface of the CAD-software the design engineer is usually working with. In this way, a selective optimization can be achieved, towards reaching the reliability target more exact and at an earlier stage of the development process.

This paper presents a feature to integrate the application of qualitative and quantitative reliability methods and data with computer-aided design continuously throughout the main stages of the product development process. The practical application of the methods is demonstrated by using an electronic clutch actuator (ECA) as an example. In the further steps it is presented the problem of confidence levels and the possibility of integration of them into a CAD-System.

Keywords: CAD, Critical part, System reliability prediction, Weibull-Distribution, Confidence level

1. INTRODUCTION

Lifetime calculation of a technical system is essential for the automotive industry to survive at the global market [1], [2]. State of the art in mechanical engineering is reliability investigation after the stage of detail design or even later when the provision of production facilities already starts. At this time the properties of single components of a technical system, i.e. the physical characteristics, the dimensions and the material of the components are already determined [3]-[6]. Due to this, only little change is feasible in order to not have to revise also other components and to affect the costs. The later the changes are realized, the higher the additional costs are. Figure 1 displays the so-called “Rule of ten”.

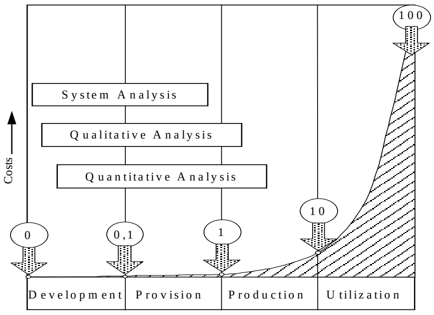


Figure 1. Rule of ten.

In early stages of the product development, modifications are easy and cost almost nothing, like modifying a line on a paper. Recent news about callbacks in the automotive industry indicates a major lack in reliability. Regarding the enormous costs of callbacks, the efforts actually being made to improve the reliability of the design are negligible. To prevent high consequential costs due to poor reliability performance, the reliability techniques must be applied continuously during the whole development process starting from the definition of the specifications.

1.1 Notation & Acronyms

B_{10}	specific lifetime for a failure probability of 10%
b	shape parameter of the Weibull distribution
$F(t)$	failure probability (cdf)
$R_i(t)$	reliability of the component i
$R_S(t)$	system reliability
T	scale parameter of the Weibull distribution
t	lifetime
t_0	failure free time (minimum lifetime)

1.2 Acronym & Abbreviation List

CAD	computer aided design
DR	design review
ECA	electronic clutch actuator
FMECA	failure mode, effects and criticality analysis
FTA	fault tree analysis
QFD	quality function deployment
VDA	Verband der Automobilindustrie (Association of vehicle manufacturers)

2. APPLICATION EXAMPLE

As a practical example, an electronic clutch actuator (ECA) was used to check the developed reliability software. Figure 2 shows the principal layout of this actuator [7]. Only the main components are marked.

With an electronic clutch system the driver can shift as usual but does not have to operate a clutch pedal. The actuation of the clutch during starting, shifting and stopping is done by means of an electronic actuator in an optimum manner. We regard the mechanical part, i.e. the actuator, of the electronic clutch system. The control unit is also integrated in this part, which receives several signals such as the shift intention recognition, the speed variation, the clutch and engine torque and the gear recognition for example. When the driver releases the accelerator pedal before shifting, the clutch torque will be reduced simultaneously. When the shift intention is detected, the clutch is almost open. The remaining time to open the clutch fully is very short and therefore allows fast gear changes. The lifetime of the mechanical parts of an electronic clutch actuator is investigated.

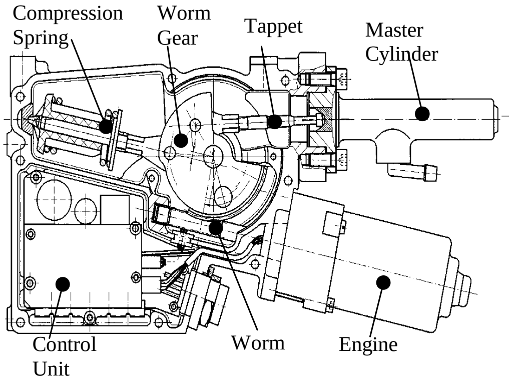


Figure 2. Principal layout of an electronic clutch actuator.

3. CA-DESIGN STAGES COMBINED WITH RELIABILITY DATA & ANALYSIS

According to the three main stages of the development process conceptual, embodiment and detail design, the management of reliability data as well as subsequent execution of reliability techniques is illustrated in this chapter. The applied qualitative and quantitative reliability methods to the example ECA are summarized in Chapter 5.

3.1 Conceptual Design

By means of a commercial CAD computer code and the additional sketch mode the stage of the conceptual design was performed. Without leaving the habitual surroundings, the designing engineer has the opportunity to execute the lifetime manager “Kosyma”. For every specified group of components a reliability data sheet is generated, which is used for the input of reliability data and its structured storage, Figure 3.

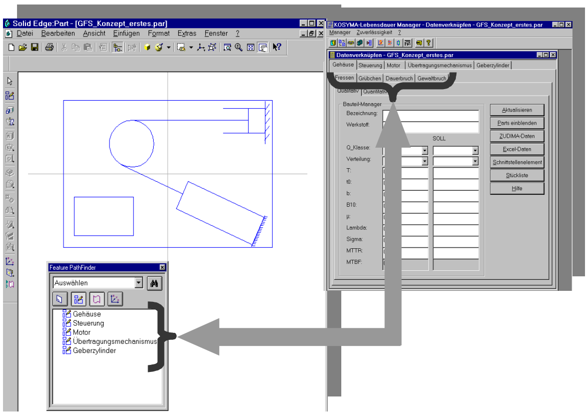
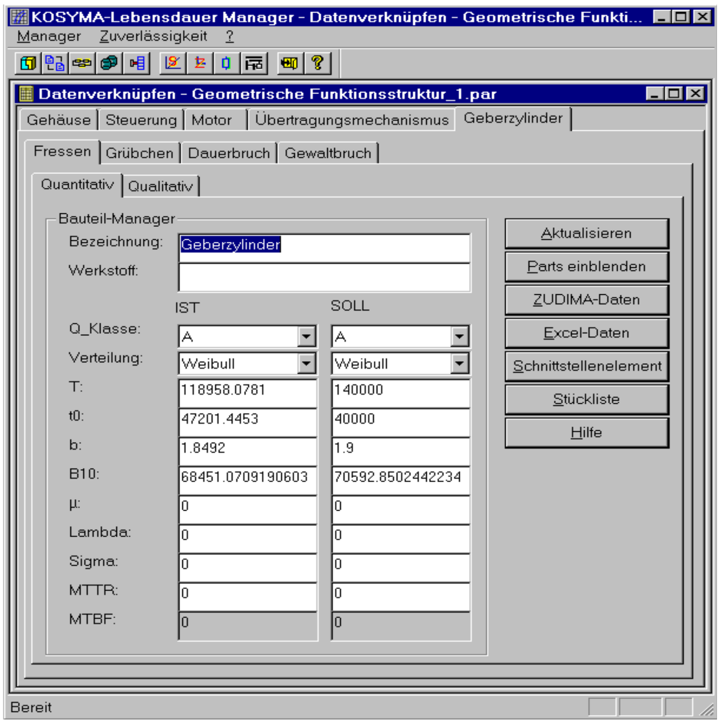


Figure 3. CAD-integrated input of reliability data.



Bezeichnung: Geberzylinder

Werkstoff:

	IST	SOLL
Q_Klasse:	A	A
Verteilung:	Weibull	Weibull
T:	118958.0781	140000
t0:	47201.4453	40000
b:	1.8492	1.9
B10:	68451.0709190603	70592.8502442234
µ:	0	0
Lambda:	0	0
Sigma:	0	0
MTTR:	0	0
MTBF:	0	0

Figure 4. Front-end of the lifetime manager – actual & desired data.

The design engineer's reliability knowledge is essential to apply the reliability techniques and to fill in the relevant reliability data, like

- General data such as name and material of the selected part,
- Qualitative data such as preferred reliability methods to apply, etc., and
- If available, quantitative data.

The quantitative data, which is given from the technical requirements, can be used as the input of the desired reliability. The register card for the quantitative data of each component is split in two columns, one of which serves as the input of actual data, the other as input of desired data according to the technical specifications, see Figure 4. This data will be employed for the reliability analysis.

In order so support the design process with the qualitative and quantitative reliability methods from the very beginning of the development process, reliability techniques can be executed to generate e.g. a first Boolean structure, Figure 5.

This structure can be used as the basis for further investigations and will be refined and changed during the ongoing CAD-process. Also the reliability data from the conceptual design will be used as the basis for the following design stages. Both, the reliability data and the preliminary results of the particular reliability method can be adapted to the following design stages, Figure 5.

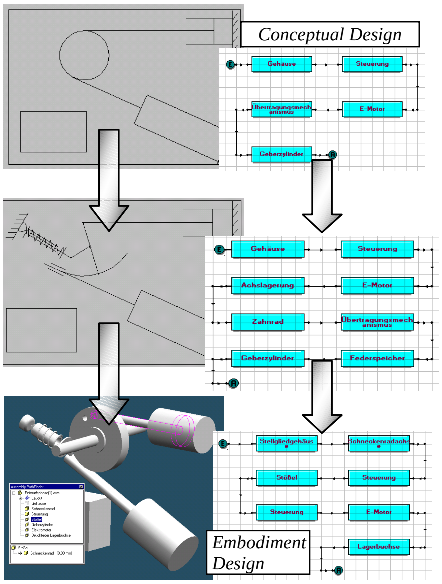


Figure 5. CAD model & Boolean structure of the conceptual and embodiment design.

3.2 Embodiment Design

As displayed at the bottom of Figure 5, the conceptual design of our example is three-dimensional extended in the stage of embodiment design. The respective Boolean structure is created based on the results of the structures according to the conceptual design.

3.3 Detail Design

In the stage of detail design, the parts and its features are elaborated. After this process, the part with the several features can be merged together to subassemblies, Figure 6. The results of the reliability methods, which were applied for the single parts, are used for the analysis of the subassembly. In Figure 6, the specific fault trees of the single components are joined together to a “subfaulttree” of the subassembly at the bottom of this Figure.

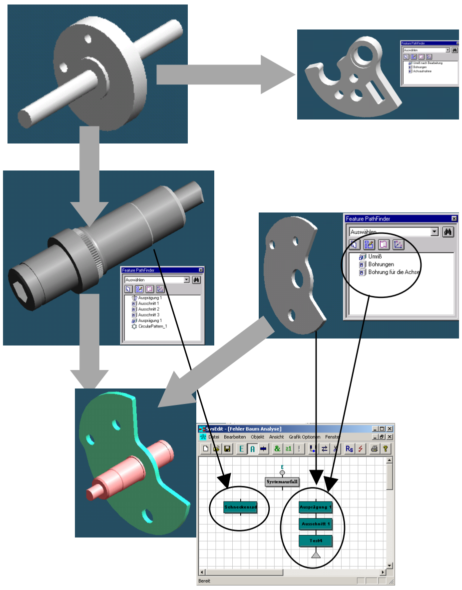


Figure 6. Detail design of single parts and subassemblies with their specific fault trees.

4. APPLIED RELIABILITY METHODS

4.1 Qualitative Reliability Analysis

- Design Review

The Design Review (DR) is a method, which is applied throughout the development process [6]. In order to apply the reliability analysis in an early stage, a so-called preliminary DR should be performed. The goal of this DR is to identify weak or fragile parts of the conceptual design in order to increase the product quality and reliability and to shorten the development period. The performance basis of the preliminary DR is a review checklist, which should concentrate on reliability topics.

- ABC-Analysis

Due to different contributions of the components to the resulting reliability of the whole system, it is not reasonable to consider all parts as equivalent in reliability investigations. Therefore, a pre-selection of critical components can be carried out with an ABC-Analysis. In [14], the method and the application is described. This kind of analysis is often used prior to an FMECA. The exclusive use of the ABC-Analysis is only applied for technically simple products.

- FMECA (*failure mode, effects and criticality analysis)*

In mechanical engineering almost all products become more and more complex, because more functionality is integrated by adding electrical components to mechanical systems. Thus, the FMECA technique is often applied after an ABC-Analysis, especially for complex technical products, such as gearboxes or engines [11], [12].

In our example, the electronic clutch actuator, which is a highly integrated complex product, an FMECA was executed subsequently to the ABC-Analysis for the pre-selected A- and B-components.

- FTA (*fault tree analysis)*

The FTA is standardized in DIN 25424 and can be performed qualitatively and quantitatively [13]. Whereas the qualitative FTA is often generated in early design stages to generally build the structure of the fault modes, the quantitative FTA is applied when the necessary data is available.

Right after the conceptual design, which is put into practice by means of the sketch mode of the CAD-Code, a qualitative FTA is performed. This illustration supports the design engineer to get a clearer overview of the structure of the different fault modes.

4.2 Quantitative Reliability Analysis

A consecutive quantitative analysis, by means of trial data, etc., has to be performed with the critical components of the system as the input [15]. In this chapter we will concentrate on the Weibull distribution for the critical mechanical parts of the example and the consecutive application of the Boolean system theory as well as a quantitative FTA.

- Weibull distribution

In literature the theory of the two-parametric and the three-parametric Weibull distribution is explained [1]-[5]. [1] proved that the three-parametric Weibull Distribution meets closer to the practical results. Results of the lifetime by means of the two-parametric Weibull distribution are always lower and do not have practical use [1]. The reliability $R(t)$

corresponds to an inverse exponential function, whereas the exponent itself has another exponent:

$$R(t) = e^{-\left(\frac{t-t_0}{T-t_0}\right)^b}, \quad t \ge t_0 \ge 0 \,.(1)$$

The parameter b is the shape parameter, t_0 the failure free time or minimum lifetime, and T the scale parameter or characteristic lifetime.

- Boolean structure

Like almost all mechanical products, the structure for the electronic clutch actuator is an exclusive serial structure. Therefore the reliability of the system can be calculated with equation

$$R_S(t) = \prod_{i=1}^{n} R_i(t) \,.(2)$$

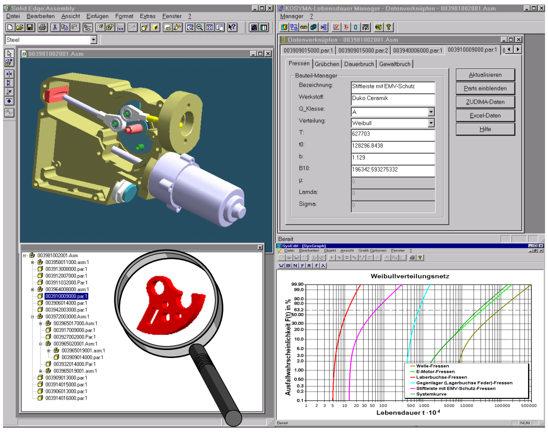
The failure free time t_{0S} of the system is equal to the smallest failure free time t_{0i} of the components, that is the worm gear with the failure mode sliding wear, t_{0S} = 1,18·10^x shift cycles. The average failure probability of the system according to the product specifications must be F_s = 0,05% for t_{0S} = 1,2·10^x shift cycles. The system shows a B_{10} lifetime of B_{10S} = 1,6·10^x shift cycles [7].

As presented, only few components of the system were investigated. Thus, it is essential to perform a qualitative analysis to focus on the main critical parts. Subsequently, a selective optimization of the weak point of the technical systems can be guaranteed.

- Quantitative FTA (*fault tree analysis*)

First, a qualitative FTA was performed by means of selecting the parts in the CAD-system and placing them in the fault tree. Since the data of the components was added in the lifetime manager, the critical path can be determined in the module “Sysedit” by means of the Weibull distribution for the different components. Within this path the critical part of the product can be seen in the Weibull probability paper.

In order to achieve a specific optimization of the product, this critical part will be unveiled in the CAD surrounding, e.g. by a different color. If the required system lifetime is not yet reached, this part has to be changed, like e.g. to broaden a gearwheel. The influence of the variation can be again visualized in the Weibull probability paper with updated data.



Bezeichnung: Stiftleiste mit EMV-Schutz
Werkstoff: Duko Ceramik
Q_Klasse: A
Verteilung: Weibull
T: 627703
t0: 128296.8438
b: 1.129
B10: 196342.593275332
μ: 0
Lamda: 0
Sigma: 0

Figure 7. Results of the CAD-integrated reliability analysis: The Weibull probability paper & the critical part of the system shown in the CAD-System.

5. FURTHER STEPS

The confidence level of the results is offen ignored in reliability studies. In early development stages the reliability prediction of the confidence level is very small, because secured results are missing for many machine components.

The confidence level becomes lower, if the test effort gets smaller, which can be seen in .

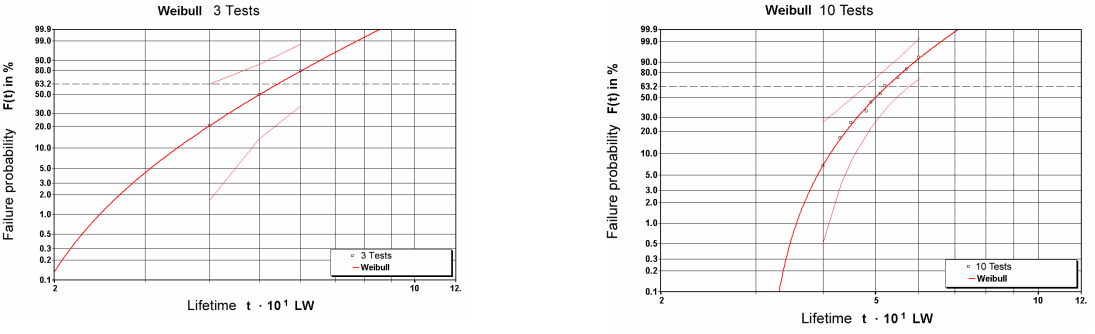


Figure 8. Tests with different sample sizes and the confidence levels

In the statistics the confidence level is often represented by confidence limits, which limit a range with a certain probability of occurrence. For machine components it is described in detail in the literature e.g. [16] how to build up the confidence intervals. The confidence levels depend on the rank, the sample size and the failure distribution. The rank is the consecutive number of the test data arranged according to failure-time. [16] uses the Chi distribution to get the confidence limits. However, for the practical application the beta distribution is preferred. In [1] und [9] tables are used for the simplification of the practical application. The determined points mark the e.g. 5% or 95% fractiles of the beta distribution. In order to get the confidence limits, the determined points have to be connected by a line. Generally, an upper and a lower confidence limit are indicated. The function of failure probability runs within the confidence limits with a well-known confidence level. By means of the confidence limits a minimum and a maximum lifetime can be determined. Further on a minima and maxima of the distribution parameters can be found, for example the shape parameter b of the two-parameter Weibull distribution.

As mentioned before, this method is restricted to derive the confidence limit of the components of the system. This method cannot be transferred to calculate the confidence limits of the system. In contrast to single unit devices, systems consist of several components with usually different sample sizes. This difference is mathematically impossible to describe during the evaluation with the beta distribution. [17] gives a detailed overview of different procedures. The methods, which are described, are not generally accepted without restrictions. For example the methods can be used only for certain distribution functions or for given system structures.

To be able to indicate confidence levels in the feature Kosyma, the data base has to be extended. In the future all available test data have to be saved for each machine component. This is particularly important for own developed components, which were already tested in a lifetime test and whose data is available in the company. If this is not possible, the sample size is stored and thus virtual rank sizes are produced. Rank sizes describe here the failure-times belonging to the ranks. This procedure is recommended particularly for purchased components or for machine components from the own company, if no documentation of the tests is available. The deviation in consequence of the produced failure-times will have only a small effect on the result of the confidence level. This mistake is acceptable for early development stages.

The third possibility, that will be offered, is to make the designers own estimation of the sample size. If no data is given for the components by the manufacturer or the machine components only available as virtual prototypes without any lifetime tests, the technical designer can produce artificial test data by an estimation of the sample size and the lifetime. With this procedure a substantial factor of uncertainty has to be considered, which is to be minimized by suitable assistance. The tolerance of this procedure is acceptable for the early development stages, because there is no data present about the machine components behaviour.

The first method shows the normal procedure to locate the confidence level of the machine component. The confidence levels give an overview about the statistical uncertainty of a tested component with a small sample size. The second and third method are consider the problem of the data availability. In the most cases there will be no test results available.

The result shows only the confidence level of the statistic uncertainty like in the first method. It is presupposed, that the estimates of the failure-times and the sample size are sure.

Since there are no generally accepted procedure for the computation of the confidence level of system reliabilities, Kosyma will be able to offer the technical designer different procedures, which are described in the literature [17]. The procedures can be divided in analytical procedures and numerical simulations. To compare the approximations of different analytical procedures as well as the numerical simulation, Kosyma will give the constructor the possibility to see results of all procedures in a diagram at the same time. Here the different tolerances of the procedures become clearly.

The results from Kosyma are shown in the program section Sysgraph in a diagram, which represents the failures over the running time. Sysgraph is extended with appropriate functionalities to be able to represent the confidence levels. For every construction unit Sysgraph can show the analytically calculated confidence limits in the existing diagram. For the system the possibility is to show the results of several indicated procedures. A valuation is not provided in Kosyma.

The aim is to give the technical designer the possibility to estimate correctly his statement about the reliability of the system by introduction of the confidence level. Information gaps in the reliability data can be promptly recognized and the security of the statement can be improved by further tests with this procedure. Besides a development target of lifetime can be achieved more economically. The functionality of the visual confidence limits improves the cost optimization, which was already presented in [15], too.

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