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# INCORPORATION OF RELIABILITY MANAGEMENT IN THE DESIGN PROCESS

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## Abstract

This paper describes a life cycle product reliability management process to facilitate decisions made during the design process. Furthermore it shows the necessity of the incorporation of reliability management in the design process while developing a new design that can achieve the expected lifetime with high quality and less failures.

The reliability management process contains qualitative and quantitative reliability methods based on warranty data, test data, condition monitoring and engineering judgement which will be fused to a closed loop failure analysis system.

Qualitative reliability methods such as the Failure Mode and Effects Analysis (FMEA) help to identify the critical components in the early stages of product conceptualization and design. The critical components of the system will be analyzed more detailed over their lifetime using different quantitative methods. Concluding, all lessons learned throughout the reliability management process will be placed in the analysis tools used in product development.

*Keywords: reliability management, warranty data, life testing, condition monitoring, qualitative methods*

# 1. Introduction

As technology advances, the customers continuously make higher demands on a product's performance and quality. Companies are exposed to an increasing competition among manufacturers. An ever decreasing development time and increasing complexity of technical products make it increasingly difficult to maintain market position [1]. Therefore it is especially important to apply design for reliability practices as early as possible. The prediction of the failure behavior of a product shall serve to let engineers incorporate reliability considerations into the design or redesign of products. In most cases the data on the actual product under design is lacking or absent. Various methods to calculate the lifetime using different data sources is presented in the following.

At the beginning of a reliability analysis a qualitative analysis has to be done in order to identify the critical components of the system that has to be analyzed and to expose possible risks in design, figure 1. The most common qualitative method to discover possible high risk issues in design and to initiate the most effective strategy to solve problems is the Failure Mode and Effects Analysis (FMEA). In order to reduce the effort of the FMEA a prioritization can be accomplished with the ABC-Analysis [1], which helps to define the critical components of a system and delimitates the complexity of the subsequent analysis.

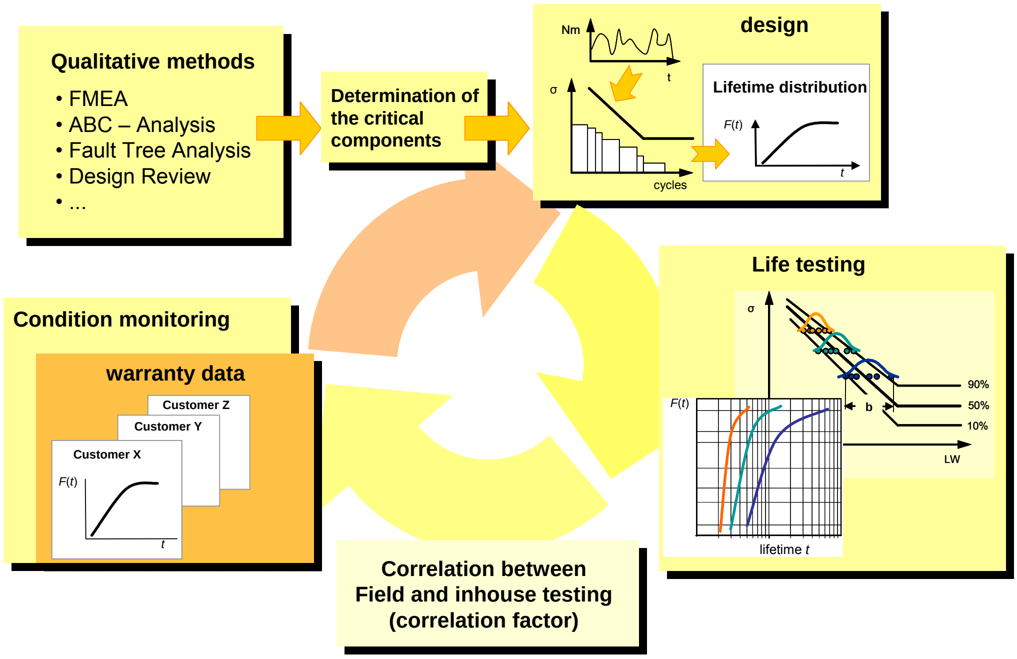



Figure 1. A full life cycle product reliability management process

The evaluation of the lifetime of a product and its components during early development stages can result from established design calculations if the two variables stress and strength are given. The results of the calculation may not be sufficiently representative, since the possible utilization and its scatter band may not be given exactly for the component and its material or the environmental factors with their coherences, such as corrosion, oxidation, salt water, temperature e.g. can not be covered completely in the calculation. The analysis of life tests demonstrate the failure behavior of a product under specified environmental conditions and can be used to verify the design calculation with regard to the major influencing factors. Unexpected failures that occur during an in-house reliability testing of prototypes can be considered directly in the design process in order to achieve a selective modification and optimization on time. Often the duration of life tests is limited due to costs and decreasing development times so that accelerated reliability testing has to be accomplished in order to provide a meaningful product life reliability estimation. The basic requirement of accelerated life testing is knowledge of the acceleration factor, often called correlation factor [2], which results from the ratio of lifetimes that arise from the two different load spectrums, e.g the load spectrum measured in the field and the load spectrum of the accelerated life test.

The failure behavior of the in-house reliability testing compared to the performance of the products in the field can vary immense. The reason for the deviation can be for example differences in the treatment. Units being tested in the labs are carefully set up and adjusted by engineers. Most end-users do not have this experience thus it can lead to much more operator-inducted failures. Another reason can be deviating conditions due to the fact that the field conditions are not exactly known.

In order to figure out the reasons for the deviation the true operating conditions in field have to be determined e.g. by condition monitoring. Using the data provided by different sensors and comparing the real lifetime with the lifetime that is calculated theoretically with the measured condition-data can help to modify and optimize the calculation in the design process.

As condition monitoring is not feasible in general for every single product in the field due to increasing costs on the one hand and the customers who do not wish the operation of their products to be monitored by the manufacturer on the other hand, field data collection and its analysis becomes very important. Field data analysis also provides an insight into the early failure behavior caused by a wrong treatment, storage and transport e.g. Those influencing parameters and the damage that has already taken place on the component before the initial operation can not be measured by sensors. Field data analysis is able to illustrate such destructive agents and can be used for reliability prediction of early failure behavior of a new product.

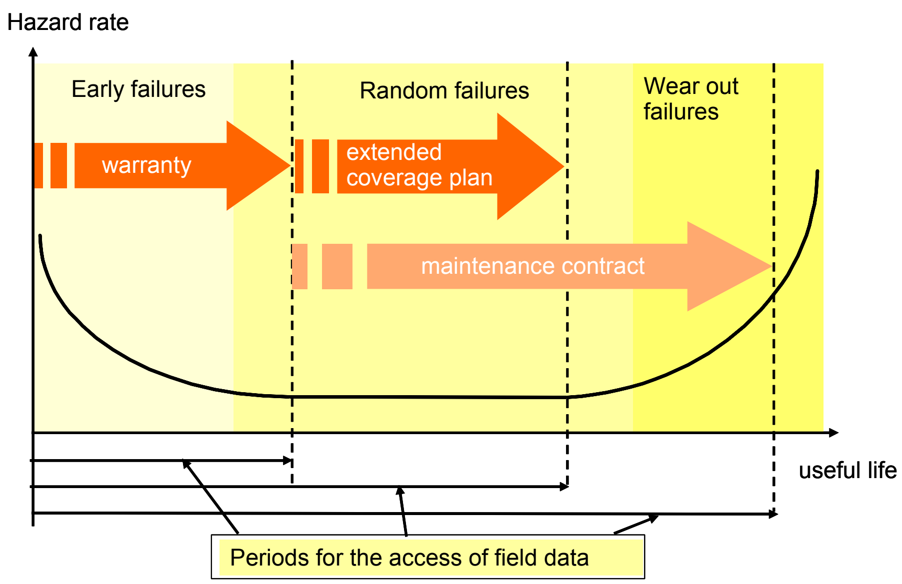



Figure 2. Long-lasting acquisition of field data [3]

For many manufacturers field data is often only available as incomplete warranty data. Mainly early failures occur during the warranty period that are caused by defects designed into or built into a product. To make a robust reliability prediction it is indispensable to collect field data over a longer period of time, which can be achieved with extended coverage plans or maintenance contracts e.g., figure 2. The analysis of field data can be accomplished with different methods, whereas the results of the estimated parameters of the lifetime distribution can differ immense depending on the applied method and the data structure that has to be analyzed. A comparison of various parametric and nonparametric estimations of lifetime distributions from incomplete warranty data has shown in [4], that it is indispensable to examine the quality of the data first and to determine the method afterwards which is appropriate for the analysis.

The results of the analysis of field data and test data will be placed in the analysis tools used in the product development in order to achieve an optimized reliability management process. The following chapters will give a detailed description of the particular reliability methods starting with the qualitative methods.

## 2. Qualitative reliability methods

Various qualitative methods such as the Failure Mode and Effects Analysis (FMEA), ABC-Analysis, qualitative Fault Tree Analysis (FTA), Design Review etc. exist to carry out reliability and safety analysis [1]. The FMEA is the most common preventive method for systematic safety and reliability analysis. The accomplishment of the FMEA can be subdivided in 5 steps, the definition of the system structure, the definition of the function structure, the failure analysis, the risk assessment and the optimization [5]. The system structure can be modelled with the help of parts lists, technical subscriptions, process flow diagrams or predecessors FMEA e.g. Often it is not reasonable to include all components in the system analysis as some components are not as critical and have no influence on the reliability of the system. A possibility to attain a prioritization of the components into three different risk groups, group A, group B and group C, is given by the ABC-Analysis see figure 3.

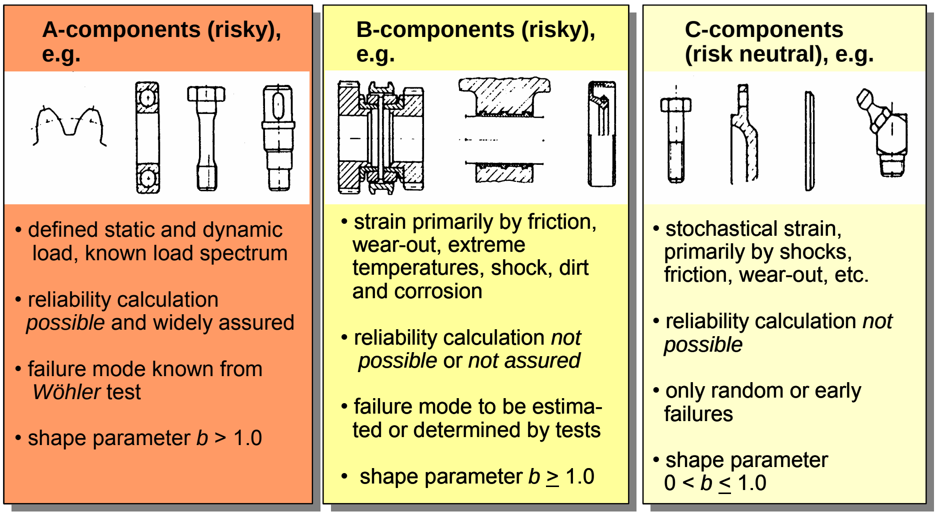



Figure 3. ABC-Analysis [1]

The components belonging to group A have the highest risk potential and will be considered first in the FMEA while the components of group B will be analyzed subsequently. It is not necessary to analyze the components that were defined to belong to group C, as they are not critical for the system.

The definition of the function structure up to the optimization will be gathered for the components belonging to group A and B. After accomplishing the ABC-Analysis and the FMEA the critical components of the system are defined and will be analyzed in detail using quantitative reliability methods.

# 3. Quantitative reliability methods

The quantitative reliability methods starting with the fatigue damage calculation in early design stages followed by the analysis of test data and field data for the verification of the theory will be introduced in the following sections.

## 3.1 Design

High reliability requirements arised from increasing product liability, higher customer demands and the minimization of failure costs have to be considered in the design of a new product, which can be accomplished by using the fatigue damage calculations in early design stages if no failure data of the current product is available yet. The basic requirement for the determination of the reliability of a product in the field is the knowledge about the true operating conditions on the one hand. Those can be investigated by simulation techniques, field testing and condition monitoring. On the other hand the utilization of the component or material has to be given in terms of a Wöhler-curve, see figure 4. The ordinate of the Wöhler-diagram represents the stress $\sigma$ and the abscissa represents the utilization $N$, the number of cycles, of the component. Every Wöhler-curve represents a defined probability of the scattered maximum utilization for a specific stress level $\sigma_i$.

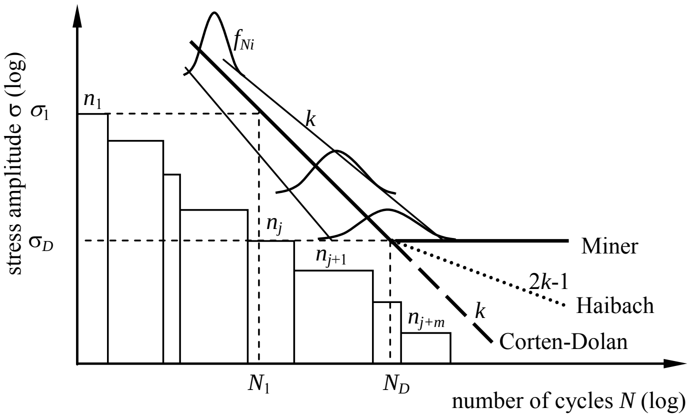



Figure 4. Wöhler-curve with three fatigue damage accumulation hypotheses and its scatter band [4]

Depending on the component that has to be analyzed and its application, different fatigue damage accumulation hypothesis such as Miner, Haibach and Corten-Dolan [6] can be applied for stress amplitudes that occur underneath the fatigue limit $\sigma_D$. Stress amplitudes below the fatigue limit either have an influence on the lifetime as it is shown for the hypothesis of Haibach and Corten-Dolan, or do not cause any damage to the component as shown for the hypothesis of Miner, figure 4.

The equation of the Wöhler-curve is defined as

$$N_i = N_D \left( \frac{\sigma_D}{\sigma_i} \right)^k \qquad for\ \sigma_i \geq \sigma_D \tag{1}$$

$$N_i = N_D \left( \frac{\sigma_D}{\sigma_i} \right)^x \qquad \text{for } \sigma_i < \sigma_D \qquad \text{with} \begin{cases} x = k & \text{(Corten} - \text{Dolan)} \\ x = 2k - 1 & \text{(Haibach)} \end{cases} \tag{2}$$

with the number of cycles $N_i$ that is bearable in the $i$-th class, the number of cycles at the beginning of the fatigue limit $N_D$, the stress amplitude $\sigma_i$ in the i-th class, the stress amplitude at the beginning of the fatigue limit $\sigma_D$ and the gradient $k$.

In order to calculate the lifetime of a component, the limit of the damage sum has to be defined first. The limit of the damage sum is a value, recommended by experts, for the occurrence of a failure and will often be defined equal or greater than one [2]

$$D = \sum \frac{n_i}{N_i} \geq 1, \tag{3}$$

with the number of cycles $n_i$ in the $i$-th class that is given from the load spectrum. If the current damage sum is lower than 1, the end of the lifetime of the component is not reached yet.

If the load spectrum is given and the damage sum for failure occurence is defined, the lifetime $L_0$ of a component in cycles can be calculated for the hypothesis of Miner:

$$L_0 = \frac{\sum n_i}{D} = N_D \frac{\sum_{i=1}^{j+m} n_i}{\sum_{i=1}^{j} n_i \left(\frac{\sigma_i}{\sigma_D}\right)^k}, \tag{4}$$

the hypothesis of Haibach:

$$L_0 = \frac{\sum n_i}{D} = N_D \frac{\sum_{i=1}^{j+m} n_i}{\sum_{i=1}^{j} n_i \left(\frac{\sigma_i}{\sigma_D}\right)^k + \sum_{i=j+1}^{j+m} n_i \left(\frac{\sigma_i}{\sigma_D}\right)^{(2k-1)}}, \tag{5}$$

and the hypothesis of Corten-Dolan:

$$L_0 = \frac{\sum n_i}{D} = N_D \frac{\sum_{i=1}^{j+m} n_i}{\sum_{i=1}^{j+m} n_i \left(\frac{\sigma_i}{\sigma_D}\right)^k}. \tag{6}$$

After calculating the lifetime of a product that arises from the load spectrum measured in the field $L_0$, it is possible to calculate the lifetime of the product for the load spectrum from the accelerated life test $L_{acc}$ in order to obtain the acceleration factor $\chi$ which results from the fraction of the two lifetimes:

$$\chi = \frac{L_0}{L_{acc}}. \tag{7}$$

If the number of cycles in the $i$-th class that is given from the load spectrum from the field $n_{i0}$ corresponds with the number of cycles in the $i$-th class that is given from the load spectrum from the accelerated test $n_{iacc}$, equation (7) can be written as follows

$$\chi = \frac{D_{acc}}{D_0}, \tag{8}$$

with the calculated damage sum $D_{acc}$ for the load spectrum from the accelerated life test and the damage sum $D_0$ for the load spectrum from the field.

The equations (4) to (6) yield a correlation for the lifetime in cycles. In order to achieve an acceleration factor relating to a time period, it has to be converted with the mean number of cycles $n_m$

$$\overline{\chi} = \chi \frac{n_{m\,acc}}{n_{m\,0}}. \tag{9}$$

It is necessary to indicate to which dimension the correlation factor is depending on, if it is the number of cycles or the duration of operation e.g., hence this can have a major influence on the quantity of the correlation factor.

## 3.2 Test data

While designing a new product and calculating the lifetime and the reliability of a system under certain conditions, the Wöhler-curves for the different components have to be known. Due to unknown Wöhler-curves for the actual component, frequently standardized Wöhler-curves for the used material will be chosen. It is necessary to verify the fictitious Wöhler-curves with test data records that are obtained from life tests, as the scatter band and the gradient can vary due to inhomogeneities in the material, tolerances, differences in the manufacturing process etc.

Test data is available for products that have already been released to the market as well as products that are still in the design stage. The analysis of the data can be accomplished by the three parameter Weibull distribution [1], with the probability density function (pdf)

$$f(t)=\frac{b}{(T-t_0)}\left(\frac{t-t_0}{T-t_0}\right)^{b-1} e^{-\left(\frac{t-t_0}{T-t_0}\right)^{b}} \; , \; 0 \le t_0 \le t \, , \tag{10}$$

with scale parameter $T$, shape parameter $b$ and location parameter $t_0$. If $t_0 = 0$ one speaks of a two parameter Weibull distribution. The hazard rate $\lambda(t)$ of a Weibull distribution is a function of time

$$\lambda(t)=\frac{f(t)}{R(t)}=\frac{b}{T-t_0}\left(\frac{t-t_0}{T-t_0}\right)^{b-1} \, , \tag{11}$$

and helps to depict all three sections of the bath-tub curve depending on the shape parameter $b$, figure 5.

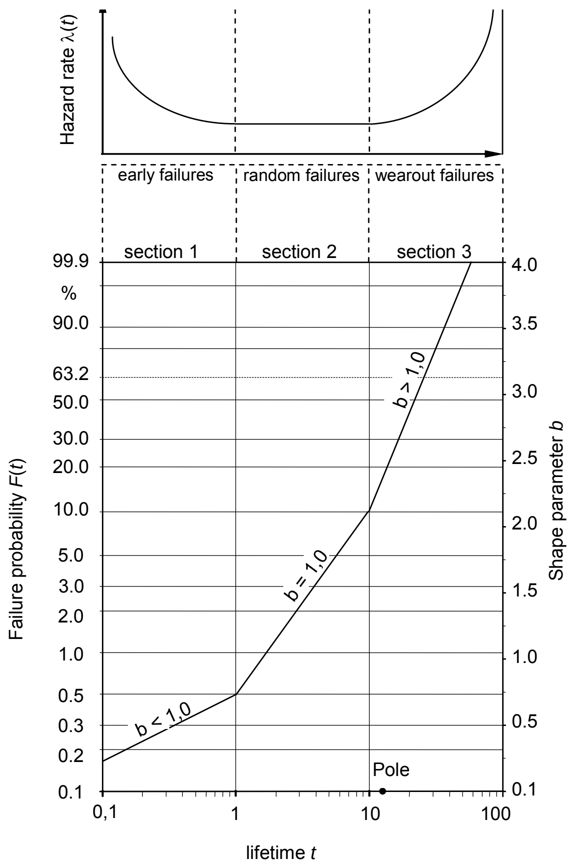



Figure 5. Failure rate $\lambda(t)$ over product lifetime

The hazard rate λ($t$) which is not constant over the product lifetime of mechanical components as shown in figure 5, can be subdivided into three sections [1]:

– Section 1 with a decreasing hazard rate ($b < 1$) represents early failures due to material or manufacturing defects, which can be determined by warranty data analysis
– Section 2 with a constant hazard rate ($b \cong 1$) represents random failures caused by sudden stresses, extreme conditions, handling errors etc, also describable by warranty data analysis
– Section 3 with an increasing hazard rate ($b > 1$) represents wear-out or aging failures. The lifetime of a component regarding a specific failure mode in this section can be calculated by using the fatigue damage calculation discussed in chapter 3.1 for a certain failure probability. If the shape parameter of the Weibull distribution is known from former tests or out of field data, the whole lifetime distribution can be illustrated.

If test data records for different stress amplitudes are available, an analysis can avail to verify the Wöhler-curves regarding the gradient and the scatter band, figure 6. Different test procedures for the determination of a Wöhler-curve are shown in [6]. The scatter band of the Wöhler-curve for stess amplitudes greater than the fatigue limit can follow a Weibull distribution e.g. [7]. The determination of the fatigue limit of mechanical components can be accomplished by the staircase method. Due to the fact that the determination of the scatter band yields a large sample size, a procedure to reduce the sample size was introduced in [8] with the assumption of a normal distributed fatigue limit.

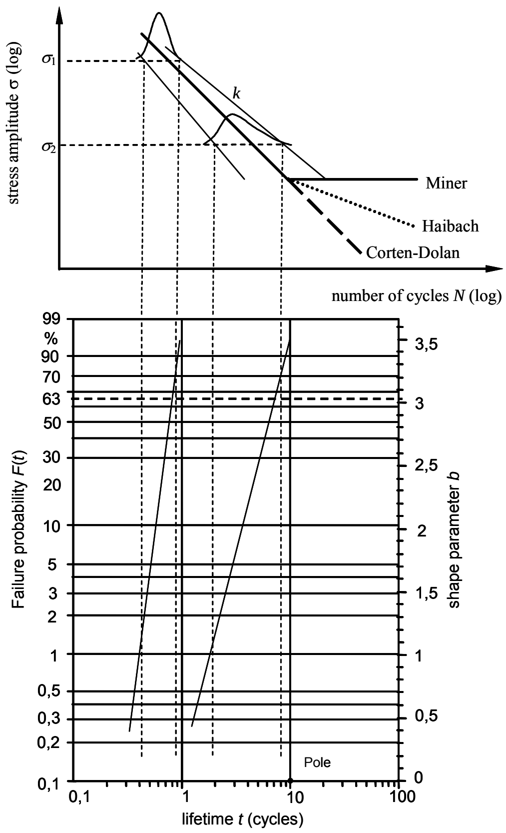



Figure 6. Wöhler-curve and its scatter band

In order to reduce the test duration, the components that have to be analyzed are exposed to higher stresses during the reliability in-house testing than within their condition in the field. In order to be able to predict the failure behavior of the component in the field, the acceleration factor has to be known. The acceleration factor is given for a specific failure mode and can not be used for different failure modes, as the failure behavior has to be the same. The acceleration factor describes how high the lifetime $t_s$ of a component is under normal operating conditions in relation to the component lifetime $t_t$ under highly stressed conditions regarding a certain failure probability $F(t)$ and is given by

$$\chi = \frac{t_s}{t_t}. \tag{12}$$

If the Weibull distributions are parallel, the acceleration factor is constant for different failure probabilities. In case of different shape parameters $b$ of the Weibull distribution, the acceleration factor has to be determined depending on the failure probabilities.

Often the real conditions in the field are not known and the acceleration factor can not be determined. Thus simulation techniques or field condition monitoring has to be accomplished in order to receive the load spectrum that includes the influencing parameters on a component. Nevertheless some influencing factors such as wrong handling or wrong mounting, damage that has already taken place during transportation etc. can not be measured by sensors. Field data analysis helps to illustrate this failure behavior.

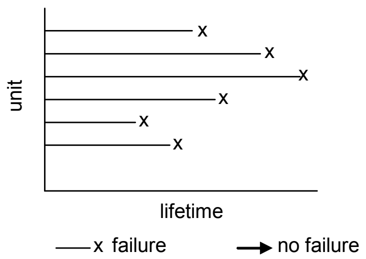
## 3.3 Field data

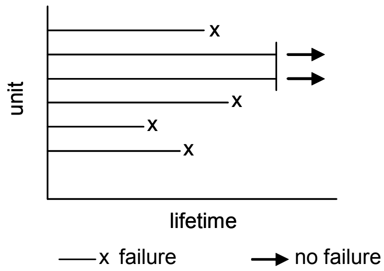
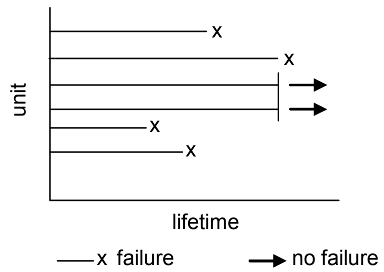
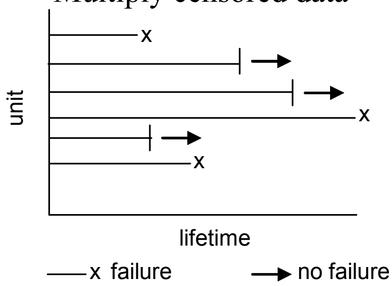
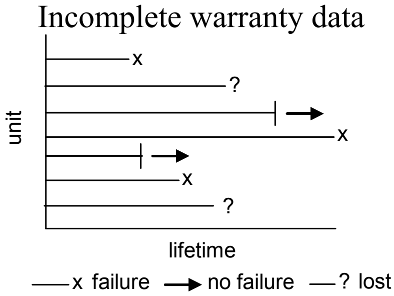
The analysis of the early-failure behavior from warranty data is useful for the estimation of the expected warranty costs and to support decisions, whether or which modifications in the product or the manufacturing process have to be introduced to eliminate this kind of failures in the future. This chapter will first give a brief introduction to the basics of the failure data analysis. Finally a robust reliability prediction with incomplete field data depending on the given data quality will be introduced.

### 3.3.1 Failure data

To ensure a robust reliability prediction, the field data collection has to be of good quality. Identification data is needed to be able to make reliability predictions regarding a specific production period. In order to be able to expose the failure mode and the failure cause, operation data has to be documented. For many industry sectors it is difficult to obtain the information that is needed as environmental conditions can vary immense and the drive performance of a product is not known e.g. Failure data can either exist as a complete sample where all components have failed or as an incomplete sample which contains failures and samples that are still intact. The different data forms are shown in table 1.

Table 1. Data analysis

| data | description | methods<br>nonparametric / parametric |
|---|---|---|
| Complete sample<br> | If a life test is accomplished until all units have failed, one speaks of a complete sample.<br>The lifetime of the failures is known. | median rank [1]:<br>$F_i \approx \frac{i-0{,}3}{n+0{,}4}$ $\forall i = 1(1)n$<br>with the failure probability $F_i$, the rank number $i$ and the sample size $n$<br><br>Maximum likelihood estimation (MLE) [1] |

| | | |
|---|---|---|
| Type I censoring<br> | A possibility to reduce the test duration can be, if the test will be stopped before all of the *n* units have failed. One speaks of a type I censoring if the test will be stopped at a predetermined time.<br>The lifetime of the failures and the censoring times is known. | median rank [1]<br>$F_i \approx \dfrac{i-0,3}{n+0,4}\ \forall i = 1(1)r$<br>with the number of failures *r*<br>MLE [21] |
| Type II censoring<br> | One speaks of a type II censoring if the test will be stopped after a predetermined number of failures.<br>The lifetime of the failures and the censoring times is known. | median rank [1]<br>$F_i \approx \dfrac{i-0,3}{n+0,4}\ \forall i = 1(1)r$<br>with the number of failures *r*<br>MLE [21] |
| Multiply censored data<br> | Multiply censored data is a collection of failures and non failures that are randomly censored such as warranty data.<br>The lifetime of the failures is known whereas the lifetime of the censoring units can be given, in terms of a drive-performance distribution e.g., or not. | The drive-performance of the censored units is missing:<br>• Sudden Death method [1]<br>The drive-performance of the censored units is known:<br>• Nelson method [9]<br>• Johnson method [10]<br>• Kaplan-Meier [11]<br>• Ceron hazard rate [12]<br>• Kuehn hazard rate [13]<br>• Bayesian hazard rate [13]<br>Using a drive-performance distribution:<br>• Meyna/Pauli [14]<br>• Joan Hu [15]<br>• Eckel [16]<br>MLE [21] |
| Incomplete warranty data<br> | Incomplete warranty data is multiply censored data with the kowledge about the lifetime of some failures and censoring units, whereas the information about the remaining units is missing. | • Suzuki [17]<br>MLE<br>• Campean (drive-performance distribution) [18]<br>• Kalbfleisch [19]<br>• Suzuki [20] |

### 3.3.2 Failure data analysis

The analysis of failure data can be accomplished by parametric methods, the maximum-likelihood estimation (MLE) e.g. [4], or nonparametric methods such as the regression analysis [1]. The difference in the methods is that the parametric methods directly estimate the parameters of the lifetime distribution while maximizing the Likelihood function whereas the nonparametric methods first calculate the failure probabilities by using an adequate method depending on the data form and afterwards they estimate the parameters of the lifetime distribution with the regression analysis [4].
Due to the fact that generally field data is lacking, especially after the end of the warranty period, methods have to be applied that are able to consider lost information of field data and can be used to perform representative reliability predictions. Various nonparametric and parametric methods that can be applied for the analysis of incomplete warranty data were investigated as shown in figure 7.

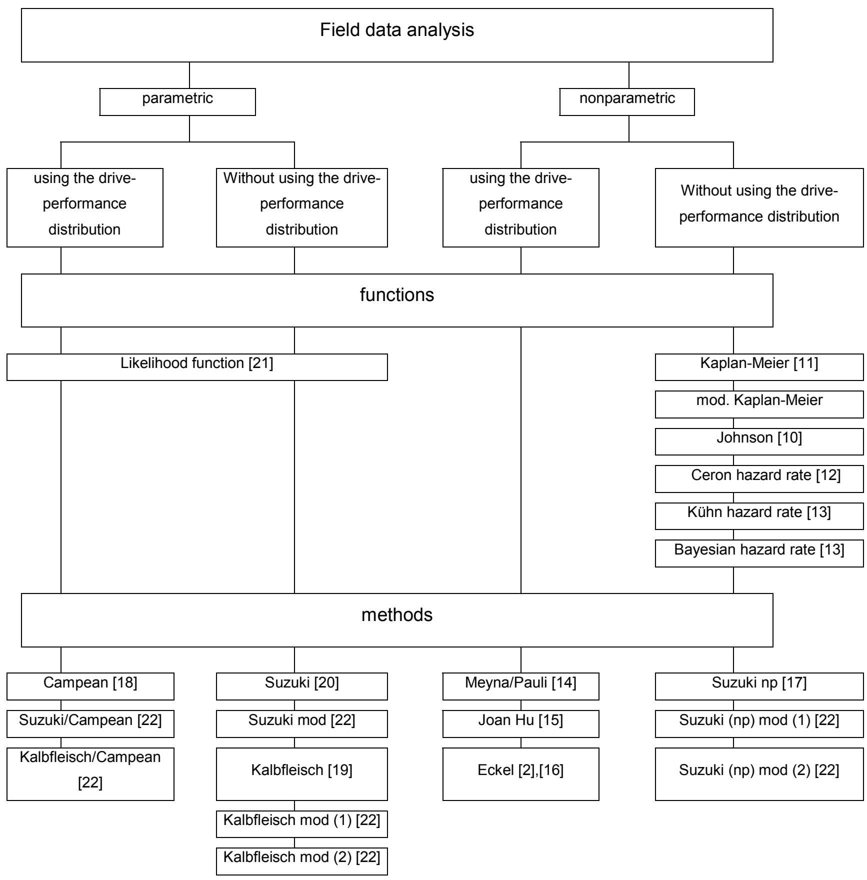



Figure 7. Parametric and nonparametric methods for the estimation of lifetime distributions

A comparison of the methods that are listed in figure 7 was gathered in [4] in order to show their applicability for a robust and representative reliability prediction depending on the data quality that is given from warranty databases. This study has shown that the results of the estimated parameters of a three parameter Weibull distribution can differ a lot depending on the applied method. The data that was used for the analysis was taken from a former project, where 34 units were analyzed with 22 failures due to the same wear out mechanism and 12 censoring times. The complete dataset was modified to various incomplete datasets, which characterize different data qualities in order to show the advantages and disadvantages of certain methods.

[4] presents a parametric and a nonparametric method which yield to excellent results for the analysis of certain data structure. In case of a high quality dataset with enough available data over the lifetime, that is evenly distributed after the warranty period, the parametric method introduced in [19] leads to a very robust estimation of the Weibull parameters. It considers the number of lost units $n_l$ in the calculation, which will be distributed to the number of failures after the warranty period $n_{u2}$ and to the number of censored units during and after the warranty period $n_c$ by the weighting factor $n_l/(n_{u2}+n_c)$. The pseudo-log-likelihood function can be written as:

$$log\,\tilde{L}(\theta)=\sum_{i=1}^{n_{u1}} log\; f(t_{u1i},\theta)+\left(1+\frac{n_l}{n_{u2}+n_c}\right)\left(\sum_{i=1}^{n_{u2}} log\; f(t_{u2i},\theta)+\sum_{i=1}^{n_c} log\, R(t_{ci},\theta)\right), \tag{13}$$

where $n_{u1}$ = number of units which failed during the warranty period, $t_{u1i}$= failure time of the $i$-th unit during the warranty period, $t_{u2i}$= failure time of the $i$-th unit after the warranty period.

The premise for the applicability of the method [19] is that the drive-performance of all failures that occur during the warranty period has to be known and a certain amount of censoring times during and after the warranty period must be given. The approach of the pseudo-log-likelihood function (13) comparing to other methods is, that additionally failure times that occur after the warranty period are integrated in the calculation. Thus the lost information can be distributed to the given information about failed and censored units.

In order to estimate the parameters of the Weibull distribution using unsteady data where only a few information about censoring and failure times are known that occur shortly after the warranty period, the Bayesian smoothed hazard function [13] in combination with the nonparametric method introduced by Suzuki in [17] leads to representative results. The Bayesian estimation for the hazard function is based on a stochastic relation between adjacent values of the interval hazard rate estimates. The Bayesian estimate for the $i$th interval hazard rate can be written as [13]

$$\tilde{\lambda}_i(t)=\frac{\alpha_i^*}{\beta_i^*}=\frac{\alpha_i+f_i}{\beta_i+M_{\Sigma i}}, \tag{14}$$

where $f_i$ is the number of failures in the $i$th interval, $M_{\Sigma i}$ is the accumulated mileage by all units in the current mileage band, $g(\alpha_i, \beta_i)$ is the Gamma prior *pdf* for the $i$th interval hazard rate and $g^*(\alpha_i^*, \beta_i^*)$ is the posterior distribution. $\alpha_i$ and $\beta_i$ can be calculated as follows:

$$\alpha_i = k_i\,\alpha_{i-1}^*, \tag{15}$$

$$\beta_i = k_i\,\beta_{i-1}^*, \tag{16}$$

with the coefficient $k_i$ that controls the passage of information through adjacent intervals, if no information passes through then $k_i \rightarrow 0$, if all information passes through then $k_i \rightarrow 1$:

$$k_i = \left(\alpha_{i-1}^*\right)^2 \Big/ \left[\left(\alpha_{i-1}^*\right)^2 + D_f^{-1} - 1\right]. \tag{17}$$

The transformation factor $D_f$ has to be subjectively chosen.

For the first interval hazard rate with no prior information the Bayesian estimator is reduced to the maximum likelihood estimate and is given as follows:

$$\lambda_1(t) = \frac{f_1}{M_{\Sigma 1}}. \tag{18}$$

Due to the fact that the hazard rate function is defined as constant within an interval $i$, a piecewise exponential estimator for the reliability function is defined as:

$$\tilde{R}_i(t) = \begin{cases} e^{-\tilde{\lambda}_1 m_1} & for\ i = 1 \\ \tilde{R}_{i-1}(t) e^{-\tilde{\lambda}_i (m_i - m_{i-1})} & for\ i > 1 \end{cases}. \tag{19}$$

The Bayesian estimation for the hazard function requires a complete dataset where all information is given. In order to analyze incomplete data, a method has to be applied that considers the lost information. A nonparametric estimation of lifetime distributions was introduced in [17]. The known data get a higher weighting in order to compensate the lost information in the calculation. The number of failures and censored units that are given after the warranty period will be adjusted with following equations:

$$\tilde{f}_i = \left[1 + \frac{n_l}{n_{u2} + n_{c2}}\right] f_i \tag{20}$$

$$\tilde{c}_i = \left[1 + \frac{n_l}{n_{u2} + n_{c2}}\right] c_i \tag{21}$$

Hence the number of failures and censored units in the $i$th interval after the warranty period increases by the weighting factor $n_l/(n_{u2}+n_{c2})$. The adjusted failure and censoring times will be considered in the Bayesian hazard rate estimation. The parameters of the three parameter Weibull distribution will be estimated by the regression analysis [1]. Depending on the chosen transformation factor the Bayesian estimation of the interval hazard rate can differ immense. [4] gives an advice about the selection of the transformation factor in order to achieve a meaningful representation of the hazard pattern for the analyzed component. Regarding these analysis it is indispensable first to examine the quality of the data and afterwards to determine which method is appropriate for the analysis.

A robust reliability prediction from field data exposes the early failure behavior of a product in the field due to wrong handling or wrong mounting e.g. which can not be described completely neither by design calculations nor by reliability in-house testing. The determination of the hazard rate over the whole product life-cycle including the early failures, random failures and wear out failures is indispensable while estimating the life-cycle costs of a product.

# 4. Summary & Conclusions

This paper shows an approach to gather a full life cycle product reliability management process in order to achieve a robust reliability prediction of a product under specific environmental conditions in early design stages. Furthermore it shall serve to let engineers to incorporate reliability considerations into the design or redesign of products and to facilitate decisions during the design process.

The reliability management process contains qualitative and quantitative reliability methods which will be fused to a closed loop failure analysis system. At the beginning a qualitative reliability analysis has to be applied in order to identify the critical components of a system. This can be accomplished in the early stages of product conceptualization and design by the FMEA and the ABC-Analysis e.g. The critical components of the system will be analyzed more detailed over their lifetime using different quantitative methods.

If no failure data is available yet, a fatigue damage calculation can be applied to expose the reliability of a product, if the true operating conditions are known. Different fatigue damage accumulation hypothesis are introduced which can be chosen depending on the component and its application. Often standardized Wöhler-curves for the material of the component will be chosen as the true Wöhler-curves for the actual component are unknown. The results of the calculation have to be verified with test data records that are obtained from accelerated life tests, as the scatter band and the gradient can vary due to inhomogeneities in the material, tolerances, differences in the manufacturing process etc. Regarding the estimation of warranty costs it is indispensable to illustrate the reliability over the whole product life-cycle including the early failures which can be accomplished by a robust field data analysis introduced in chapter 3.3.2.

Concluding, all lessons learned throughout the reliability management process have to be placed in the analysis tools used in product development to achieve a representative reliability prediction of the product in field.

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