

Quality Management in the Automotive Industry

Reliability Assurance of Car Manufacturers and Suppliers

Part 3

Case Studies in the Reliability control loop

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Case Studies in the Reliability control loop

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Foreword to the 1st edition

Volume 3 Part 3 was created to facilitate a practice-oriented introduction to the topic of reliability engineering and serves as a supplement to Volume 3 Part 1 and Volume 3 Part 2. Based on key questions and a consistent notional example (wheel bearing), it provides a clear introduction to the work on reliability in the product life cycle of the automotive and supplier industry. Additional, purely notional special examples enable a deeper examination of the topic. All the examples shown in this volume are used purely to illustrate the methods and make no claim to universal validity.

An important motivation for the creation of this volume was to highlight the interconnections and interdependencies of key methods, data and information flows across different phases of the reliability work in the product life cycle. In this way, information from every phase (concept, development, production and use phase) is made usable in terms of added value for all other phases in the product life cycle.

The aim is to illustrate the practical application, interaction and understanding of the standard methods in the reliability control loop from the OEM and supplier point of view. In all the notional case examples, attention was paid to both reproducibility and comprehensibility of the calculation methods and also to the relevant assumptions made for application of the methods. The user thus obtains a consistent system relating to processes and methods of reliability work.

The data used were generated by means of simulations using parameters close to reality.

In this volume, the focus is placed on the technical aspects of the reliability analysis and consideration of the commercial aspects is deliberately omitted.

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Formula symbols, units and functions used

$(\alpha\beta)vm$	Effect of the parameter value vm of the interaction V*M
$(\alpha\gamma)vp$	Effect of the parameter value vp of the interaction V*P
$(\beta\gamma)mp$	Effect of the parameter value mp of the interaction M*P
a_i	Lifetime factor temperature-dependent
A_{MIS}	Number of accumulated failures for each MIS line
b	Shape parameter of the Weibull distribution (slope in the Weibull grid)
b^*	Coefficient of linear function
B_{10}	Operating time at which 10% of the units have failed
B_{50}	Operating time at which 50% of the units have failed => median
C_{pk}	Process capability index
DF	Degrees of freedom
e^*	Coefficient of linear function
E_a	Activation energy in eV
$F(t)$	Failure probability as a function of time
F_{Veh}	Load force in the vehicle
F_{GW}	Failure probability for warranty period
F_i	Load force
$F_{corr}(t)$	Failure probability corrected
$F_{MCS}(t)$	Failure probability with Monte Carlo simulation
F_{MIS}	Failure probability for MIS
F_V	Probability of vehicle delay
H	Cumulative frequency
i_{virt}	Virtual rank
k	Boltzmann constant
κ	Time acceleration factor
l	Positional parameter reliability growth
L_{hr}	Lifetime in h
L_V	Lifetime ratio
M_i	Claim delay time
MIS	Months In Service
$MTTF$	Mean Time To Failure

$MTTF_{cur}$	Current Mean Time To Failure
$MTTF_{target}$	Target Mean Time To Failure
m_{ln}	Logarithmic mean
n	Number (test values, failures, production quantity, speed, etc.)
N	Load-cycles-to-failure, number of failures
n_{equiv}	Equivalent speed
n_{tot}	Total sample size
n_i	Speed level
n_{prod}	Production quantity
P_A	Confidence level or upper confidence limit
P_{equiv}	Equivalent bearing load
p	Lifetime exponent (corresponds to S-N exponent k)
q_i	Percentage
$R(t)$	Reliability, survival probability
R_0	Reliability of predecessor model for confidence level 63.2%
$R_{tot, PA50}$	Overall reliability with confidence limit 50%
$R_{tot, PA90}$	Overall reliability with confidence limit 90%
S_{ln}	Logarithmic standard deviation
T	Temperature
T	Characteristic lifetime of the Weibull distribution
t	Operating time variable (e.g. driven distance, operating hours, load cycles, etc.)
t^*	Operating time standardized to required lifetime or log. lifetime
T^*	Characteristic lifetime standardized to required lifetime
t_{10}	Operating time at which 10% of the units have failed (formerly B_{10})
t_{req}	Required lifetime (h, cycles, km, etc.)
t_{mean}	Average lifetime
t_0	Failure-free time of the Weibull distribution
t_p	Overall test time
t_{accel}	Lifetime under accelerated loads
t_{test}	Test period, test operating hours, test cycles, test mileage
V_i	Registration delay time

α_v	Effect of the parameter value v of the factor vehicle
β_m	Effect of the parameter value m of the factor market
γ_p	Effect of the parameter value p of the factor production month
ε_{vmp}	Residual error (variation not explained by the model)
μ	Mean value over all failure rates
$\emptyset$	Average, on average

List of Abbreviations

ALT	Accelerated Life Test
ASIC	Application-specific integrated circuit
EoL	End of Line (test)
FIFO	First-In-First-Out
FMEA	Failure Mode and Effects Analysis
KPI	Key Performance Indicator
HALT	Highly Accelerated Life Test
HASA	Highly Accelerated Stress Analysis
HASS	Highly Accelerated Stress Screening
MCS	Monte Carlo Simulation
MLE	Maximum Likelihood Estimation
OEM	Original Equipment Manufacturer
PDP	Product development process
prod	Production, produces, produced
RGM	Reliability Growth Management
SOP	Start of Production
SPC	Statistical Process Control
Veh	Vehicle
Vehs	Vehicles

1 Introduction

Reliability is the most important purchasing criterion for customers [DAT]. Thus, for economic reasons alone, reliable products will achieve a competitive advantage in the market.

It is very important for manufacturers to define reliability targets and to track them systematically throughout the life cycle of products so that they can offer reliable products. This not only promotes a high level of customer satisfaction but also the possibility of complying with legal requirements.

Reliability is defined in this volume as the fulfillment of expectations regarding a product's functionality from the viewpoint of the user/customer and also from the manufacturer's viewpoint over the entire lifetime of a product.

The customers expectations regarding a product's reliability can vary widely depending on the conditions of use and the market. In general, the expectations are that long-term functionality, safety, maintainability and appropriate repair costs will be guaranteed throughout the product life cycle. In addition to this are expectations regarding the enjoyment of long-term use, fulfillment of legal requirements and cultural as well as political expectations, e.g. in respect of the product's sustainability and environmental compatibility.

The manufacturer's expectations regarding a product's reliability consist on the one hand of fulfilling the above-mentioned customer and other requirements (legal/social) and on the other hand of fulfilling his own interests.

The problem, however, is that there is only limited information about deviations from the expectations for a product's reliability. In the majority of cases, data from the warranty and goodwill period are used. Beyond this, the information situation is lacking or only emerges due to a market pressure, belatedly and limited to individual problems only. This means that new products cannot be adequately designed to fulfill the expectations of customers and manufacturers. This also applies to the long-term behavior of the products.

In principle, products are reliable (reliability target is not exceeded) if the actual use (stress) does not exceed the product's actual, statistically distributed strength (load capability profile). In order to make it possible to describe a product's reliability, it is necessary to record the stress and the strengths for a product systematically, including its components and assemblies. Based on this, a product's reliability targets can be planned and developed during its lifetime. Compliance with these reliability targets has to be monitored over the entire life cycle and, in the event of any deviations upwards or downwards, the causative influences (e.g. market or usage behavior or production influences which affect the product's robustness) have to be determined. This knowledge must then be channeled back systematically into product development and production phase to close the reliability control loop.

To implement this approach, section 2 introduces the reliability control loop with a rough process description and a possible data model. It records systematically all components of a product with their actual stresses and strenght. It further permits the feedback of knowledge based on deviations from the reliability target (failure patterns with parameter value) to the concept, development and production phase. Section 3 runs through a complete example of a "wheel bearing" across all phases of the life cycle based on the reliability control loop in order to illustrate the procedure under conditions close to reality. Section 4 contains special examples for the individual phases of the product life cycle. Fig. 1.1 outlines the reliability control loop.

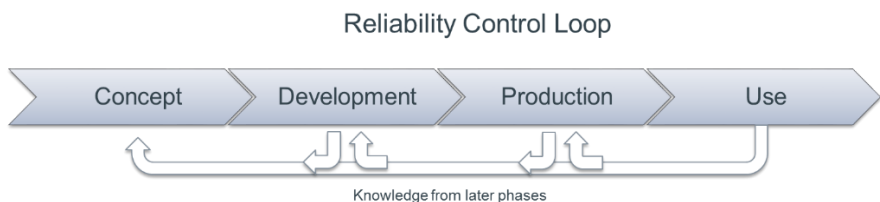


Fig. 1.1: Schematic diagram of the reliability control loop

The main objective of the loop is to provide information from the entire lifetime of a product so that it is possible to draw conclusions for adjusting the reliability targets, e.g. during the development of new products, considering the long-term and short-term behavior. In this way, as markets

and customers increase their requirements for reliability – and therefore for the creation of more reliable products – it is possible to secure entrepreneurial goals at an earlier stage.

The increasing development of new business models also calls for predictable reliability values as they have a direct impact on economic success. Operator models in particular should be mentioned as an example.

Data availability with regard to routes, speed profiles, locations, operating states and environmental conditions will increase in the future as digitalization progresses. The reliability control loop with the data model creates a structured framework for this, making this information usable for real-time status diagnoses, residual lifetime models and online reliability. However, it is also important to pay attention to the legal framework, which is not yet completely clarified in respect of data usage at present.

2 Basic approaches in the reliability control loop

2.1 Basic principles of the reliability control loop

The reliability control loop describes the relations and dependencies as well as the information flows within the entire life cycle of a product (system) and its assemblies in terms of characteristics that describe reliability. The starting point is the definition of reliability targets. The reliability target for a system is developed, confirmed (concept and development phase) and monitored (production and use phase). Deviations are introduced into the reliability control loop as information so that the reliability target can be readjusted. The reliability target is therefore shaped by the expectations of customers, the manufacturer, the legislation and other expectations, such as environmental friendliness and reputation. For the purpose of simplification, only the technical characteristics of reliability are considered here.

In general, a system is made up of subsystems, components and assemblies. Depending on the role (OEM, tier 1 supplier, tier 2 supplier, etc.), the system is considered as a delivered unit. The smallest element to be considered in the relevant roles is the purchased part that can not be broken down further.

With regard to reliability, the customers as users of the vehicle only expect a certain number of failures over the lifetime. These expectations can be expressed in the characteristic total number of failures per vehicle over the service life. This can be further expanded via the characteristic total repair costs incurred over the service life, in relation to the vehicle.

From the manufacturer's point of view, fulfillment of the individual user's expectations and evaluation of the quality situation of all vehicles similar to the individual vehicle are just as important as the total repair costs for the vehicle population considered. The expectations here are in compliance with a quality or reliability target over the service life and profitability of the products in relation to the expected life cycle costs per vehicle produced.

The supplier's view, e.g. of assemblies, is similar to the manufacturer's view but is based on the pro rata quantities he has produced and supplied. From this point of view, it is also necessary to take into account that similar

assemblies are delivered to different manufacturers and may be subject to different stresses there. The situation where a manufacturer has several suppliers is also not without its problems. On the one hand, the manufacturer cannot be certain whether both suppliers have the same quality standard and on the other hand, the individual supplier does not know which subsets of his products have been installed in a specific vehicle population for specific user groups.

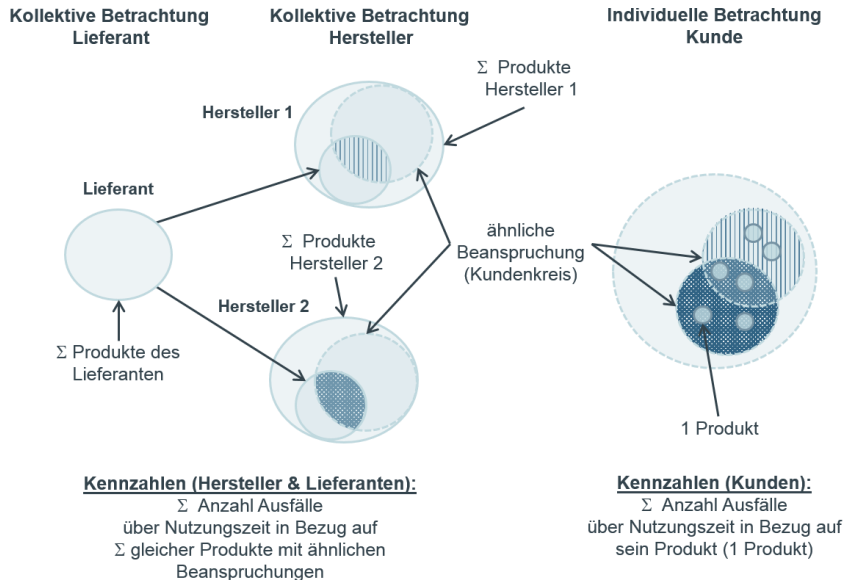


Fig. 2.1: Schematic illustration of the manufacturer's, supplier's and customer's point of view

2.1.1 Questions in the concept phase

The following typical questions arise within the reliability control loop during the concept phase:

- What reliability target is to be defined for the system, taking into account customer expectations, competition and market analyses, life cycle costs as well as legal requirements and safety aspects for example?

- Which components/assemblies need to be considered individually over the entire reliability control loop, and how can the remaining quantities with their influences on the overall reliability target be recorded statistically?
- How is it possible to ensure that the overall reliability target is met and readjusted for follow-up products, taking all components and their interactions into account?
- How can the reliability targets be met when changes are made to the strength (aging processes, spare parts) and also to the stresses themselves (change in usage behavior, legislative changes)?
- What insights can be gained from field data of similar products for setting reliability targets (e.g. production variation, tolerance specifications, detection of deviations)?
- How is it possible to document the information about the assumptions made on definition of the reliability targets and changes to them which arise from the following phases (data model)?
- Which information from the concept phase is to be condensed and how (e.g. key figures)? To which phase is it to be transferred to?

In the concept phase, the reliability target of the system has to be specified based on the assumption of identified load spectra and planned strength of the system. The system reliability target is defined in an iterative process over the total number of reliability targets for the subsystems and components through to the reliability targets for the assemblies. This leads to the structure of reliability targets for the assemblies in the system. Within the system, there may be a virtual subsystem that combines the assemblies which should not be considered individually, for example due to very low failure rates and lack of legal or safety-related requirements.

The knowledge gained from the usage, production and development of predecessor models and information obtained from the concept FMEA is used to build up the structure and estimate the system reliability target.

The key reliability figures of the downstream phases are required for the assessment. Sound knowledge of the reliability engineering methods from all phases is necessary in order to interpret them. From each phase, the relation to the reliability targets has to be established for the reliability-relevant characteristics considered:

1. Concept phase: Estimating the reliability target by considering predecessor products, inclusion of sales planning to expand/change the usage and market specifics and use of extrapolations
2. Development phase: Reviewing previous testing in relation to mapping of the current stresses (user groups), plausibility check using road and bench tests (e.g. S-N (Wöhler)) of planned technical improvements or expansions as well as extension of the stress by new user groups
3. Production phase: Reviewing production quality variations in predecessors and estimating whether the production quality can be brought up to a better level
4. Use phase: Reviewing the current field situation of the predecessor, if necessary extrapolating the current situation to longer service life and making a comparison between defined reliability targets and current field situation of the predecessor

By understanding these relations, it is possible to develop a requirements specification much more accurately in the concept phase, which improves the further development, confirmation and tracking of reliability targets.

2.1.2 Questions in the development phase

Based on the requirements specification, the reliability structure and targets will be specified and confirmed during development.

The following typical questions arise within the reliability control loop during development:

- How can the reliability targets from the concept phase be implemented and confirmed?
- How can the loads arising in the later use phase be identified, quantified and grouped together into load spectra ?
- How is it possible to ensure that all components of the system are recorded and assessed with respect to the influence on the reliability target?
- Which failure mechanisms can be expected and how are they causally linked to the stresses/load spectra already established?
- How will the remaining scopes which are not considered separately be systematically recorded and assessed?
- Which types of tests are to be carried out at which aggregation level in order to cover all failure mechanisms?
- Which testing effort is required to confirm the chronological sequence of the reliability targets quantitatively (method, test time, time acceleration, number of subjects), even allowing for changing load spectra (robustness) and strength limits (e.g. wear of seals)?
- How will the test results be summarized into a statement about the overall reliability which will be compared with the reliability target?
- How is it possible to extrapolate from bench tests to the field? How can conclusions about the bench tests be drawn from isolated failures in the field?
- What should be done if the reliability target is not met?
- Which specifications are to be defined for the later production phase and/or field monitoring?
- How and where will reliability-relevant characteristics be specified and documented?

In principle, standardized load spectra will be developed in the development phase. They will be tested in relation to the load capacity of the system, subsystem, components or assemblies with tolerance sample prototypes, for example by means of accelerated tests in order to confirm the defined reliability targets. In this case, it is possible to generate a particularly high benefit if all relevant findings regarding the actual strengths and stresses from the production and/or use phase of the affected or even similar products are integrated and used. As a result, it is sometimes possible to compare the real field load directly with the abstract reliability target. Thus it becomes possible to implement a control and diversification of the load spectra in variants for the system. Overall, the reliability target from the concept phase is verified in this phase and product qualification for series production is also carried out. In addition, the reliability-relevant characteristic tolerances are derived and handed over as the basis for complying with the defined load capacities for the production phase.

2.1.3 Questions in the production phase

The following typical questions arise within the reliability control loop during the production phase:

- What is the correlation between the produced component quality (reliability-relevant characteristics) and the field quality? How do deviations in the characteristics affect the field quality? How can the reliability target in use be transferred to the reliability target in production?
- Are the special characteristics defined in the process FMEA completely recorded and do they cover the reliability-relevant characteristics completely?
- Are the processes which influence the reliability-relevant characteristics controlled (stable) and capable (sufficiently low spread)?
- How can higher-level test scenarios be set up to test the reliability targets of assemblies?

In general terms, compliance with the defined load capacity of the system has to be ensured in this phase by (statistical) characteristics monitoring and also in-line reliability tests using the load spectra defined in development. Monitoring and proof of process capability for the specified reliability-relevant characteristics are carried out to prevent negative effects on product reliability and to be able to identify process variances and deviations at an early stage. In addition feedback about and assessment of the risks/effects on reliability of any process changes carried out are required particularly in ramp-up.

The specified and confirmed reliability targets have to be monitored regularly and at preferably short time intervals in the use phase. Deviations should be identified promptly in order to be re-entered as information in the reliability control loop so that the reliability target can be readjusted. By analyzing the data from the use phase, it is necessary to deduce to what extent deviations are to be assigned to the in-house manufacturing process or the upstream supplier process. For non-capable processes, it may be necessary to make adjustments to the specification in the development process.

2.1.4 Questions in the use phase

The following typical questions arise within the reliability control loop during the use phase:

- How does the system with its components and assemblies behave in the field from the customer's, manufacturer's and supplier's point of view?
- How can the failure behavior in the field be described statistically?
- What are the dependencies in the supply chain? How and where are the reliability-describing characteristics and the change history documented?

- How is it possible to identify possible causes of deviations (non-identified stress or insufficient strength due to design of tolerances or production variations)?
- How can deviations from the defined reliability targets be identified at an early stage, for example by observing individual user groups?
- How is it possible to generate and update standardized error codes in all phases (data model)?
- How is it possible to analyze and predict complaints using a structured and standardized approach? How is it possible to distinguish between different failure mechanisms?
- How is it possible to observe the field actively?
- How and in which way is it possible to feed back the information regarding the reliability-relevant characteristics from the use phase to the other phases of the reliability control loop? Which complaints are caused by production, development or concept?
- How is it possible to predict the extent of field failures?
- What significance does the information of deviation from the reliability targets have from the manufacturer's, supplier's and customer's point of view?
- What measures are to be defined and how can their effectiveness be checked and demonstrated?

Monitoring to ensure compliance with the specified reliability targets takes place in the use phase. If deviations are detected, the reasons have to be identified. In particular, it is possible to distinguish between early, random or wear failures. In the case of early failures, the failure rate (number of failures due to number of intact units in the field) increases sharply just after initial operation and decreases again over time. For example, these are problems often caused by production (manufacturing and assembly).

In the case of random failures, the failure rate is constant over time. These are often caused by the coincidence of several influencing factors, such as incorrect fault diagnoses, NTF (no trouble found) cases, improper use or incorrect disassembling.

Wear failures display an increasing failure rate over time. The reasons are mainly that damage parameters and time acceleration factors were not completely identified in the test phase or that the design is not robust or suitable for production, e.g. due to lack of tolerance sample testing. Wear failures occur when the combination of stress/strength has not been sufficiently considered in the overall design. Strength problems can be caused by production or design. The considerations regarding strength are basically part of the design FMEA. In the case of complex stresses/interactions it is necessary to identify changes in the stress at an early stage by systematic field monitoring.

In addition to identifying deviations from the reliability target due to the failure mechanisms just described, active field monitoring has to be carried out. This can also mean observing parts which are not yet defective or recalling them from the field. The residual lifetime of these parts must be determined and compared with the damaged parts and the test conditions. Thus any deviations from the specified behavior can be identified. It is possible to reflect knowledge about the system's failure behavior from actual use, based on higher quantities and secured processes gained from production, back into the affected phases of concept, development and production. This allows, for example, the identification of unstable production processes. Identifying the stress/strength results is an important information gain for the accelerated tests used in development. The current series can therefore be improved. For new developments, the knowledge gained about the design during the use phase can be re-incorporated into the concept phase. It can also be used as a basis for further business models such as maintenance contracts and operator models.

2.1.5 Principles in the reliability control loop

The reliability control loop connects the phases described earlier and ensures that the reliability of products is designed efficiently and effectively along the entire life cycle. The reliability control loop emerges mainly due to the exchange of information regarding the assumed stresses/strengths and

the current stresses/strengths experienced in relation to a continuous consideration of reliability targets. The following Fig. 2.2 illustrates the reliability control loop with each product life phase schematically.

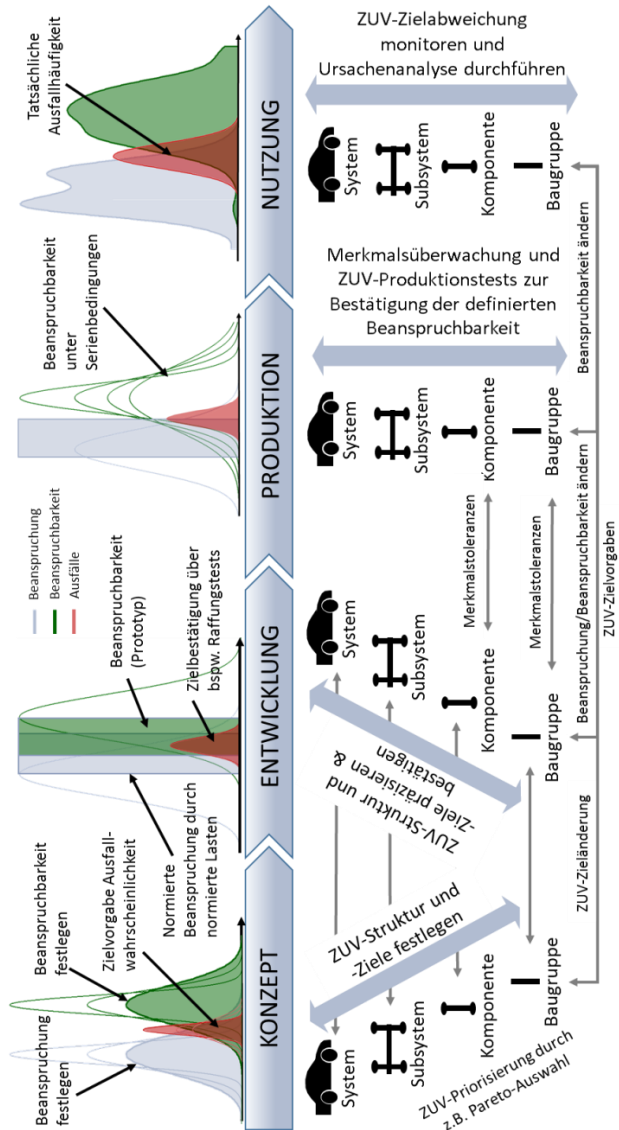


Fig. 2.2: Schematic illustration of the reliability control loop according to [Pasch et al. 2017]

2.2 Processes in the reliability control loop

2.2.1 Concept phase



The decision to introduce a new product or a modification/new edition of an existing product is a trigger for reliability work. In a first step, the reliability target is defined from the manufacturer's and customer's point of view (e.g. failures per vehicle). Information from sales (how many vehicles are being driven under which environmental conditions and by which customer groups?) must be taken into account as well as other information from the company. The aim is to find out which stresses are to be expected, whether the production quality is adequate, whether new technological changes are imminent and/or whether there is a strategic decision to adjust the reliability target. Considering predecessor products can make it easier to achieve this.

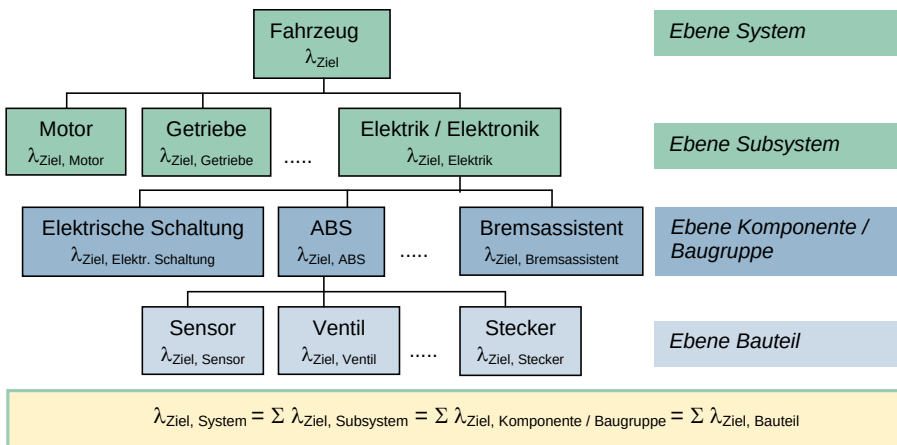


Fig. 2.3: Hierarchy levels of the system and the reliability targets

Once the strategic reliability target for the system has been defined, the subsystems have to be identified so that the reliability target can be allocated among them on a pro rata basis. After specifying the subsystem reliability targets, they can be estimated, for example, by means of reliability calculations and experience obtained from predecessor subsystems or similar subsystems. However, aggregation of the subsystem targets must not exceed the specified overall target.

The components and assemblies are identified within the subsystems and used to build up the reliability structure per subsystem. The reliability structure is used in the next step as the basis for implementing the design FMEA which allows prioritization of the components and assemblies for achieving the subsystem's reliability target. The components and assemblies whose attainment of the reliability target has a significant influence on the subsystem are specified based on prioritization. They are then considered separately. The components and assemblies not to be considered separately are grouped into a collective.

For both the components and assemblies to be considered separately and also for the collective, the reliability targets have to be determined proportionately to the reliability target of the subsystem. In this case, re-aggregation of the reliability targets of the components and assemblies must not exceed the reliability target of the subsystem. If it is foreseeable at this point that the subsystem's reliability target will not be met, it is required to adjust the subsystem's reliability target. The effects on the system's reliability target have to be discussed, resulting in a redistribution within the subsystems, if necessary.

After specification of the reliability targets at all levels, the reliability targets of the components and assemblies are clearly defined, taking into account the specific general requirements. For this, the specific general requirements for the components and assemblies are determined, considering the environmental conditions, the volume figure, the manufacturer's conditions, the use conditions and the legal conditions. Based on this, it is possible to derive qualitative and quantitative component and assembly requirements. This is the starting point for qualitative determination of the stresses/strengths of the components and assemblies.

In the next step, the permissible failure probability must be clearly defined by comparing the stresses (total substresses from all user groups, e.g. various markets or taxis and non-taxis, see section 0) and strengths. It is to identify and document which substresses have which effect on the overall stress. If the failure probability determined corresponds to the specified reliability target values for the overall stress, the reliability targets from the system through to the assemblies are transferred to the requirements specification. If they do not correspond to the specified targets, it must be examined whether convergence with the specified target is predictable by screening out load spectra or by increasing the strengths of the components or assemblies. If no convergence is expected, the separately considered components and assemblies and their reliability target values have to be changed. This may have effects on the reliability targets of the subsystems through to the reliability target of the system.

This iterative process has to be repeated until all reliability targets from the system through to the assemblies have been precisely defined and transferred to the requirements specification.

2.2.2 Development phase



Based on the requirements specification, the reliability targets are further developed in the development phase and confirmed by testing and calculation/simulation. In the first step, the design FMEA is created, the reliability-relevant characteristics being specified in the process, and a traceability concept is derived. As a result, the reliability targets for the components and assemblies to be considered are developed and finally related to the system level.

After prototype development, their strength and the stresses occurring must be detailed.

If the different stresses occurring are known in the realistic driving profile, they can be combined to load spectra (individual and mixed load spectra). If they are not available, they must be determined, e.g. from calculations and simulations taking into account the environmental conditions and the real use conditions.

If the strength of the components and assemblies is unknown, it has to be determined by means of calculations, representative tests and experiences from predecessor models so that adequate dimensioning is guaranteed. If the strength is not adequate, a change has to be made to the component or assembly, for example a material change or design modifications.

An initial lifetime estimation has to be carried out if lifetime models based on superimposing the determined stresses and strengths can be applied. If the calculation shows that the reliability target stipulated in the requirements specification is not met, it has to be assessed whether increasing the sample size or extending the test period achieves the target. Otherwise, it must be checked whether it is possible to change the strength (increase component strength by a design change or by suitable materials).

Appropriate measures should be taken to reduce the stress acting on the component, if possible. Alternatively, for very high stresses, a separate variant can be derived or a preventive maintenance interval can be specified.

Should the reliability targets not be achievable, e.g. for economic reasons, the specification from the concept phase must be adjusted, communicated and approved.

Verification of the lifetime must be provided, as far as possible, by testing. In the case of very complex assemblies, the tests may also extend to the individual components (e.g. drivetrain). The overall reliability is then derived from the reliability block diagram (see [VDA Vol. 3.2, 2016] Section 6.2).

For this, assemblies and components are considered and, in a first step, the main failure modes and their causes are derived from the FMEA and/or the use phase of similar components (e.g. predecessors). The causal relation between the failure modes and failure causes (stresses) can be described statistically, e.g. by Weibull parameters. It is necessary to derive

appropriate test scenarios that can reconstruct the failure modes occurring in the field based on the expected causalities. The prevailing loads in test scenarios within the lifetime have to be transferred into a correspondingly complex stress in the test. Enough test samples and a corresponding test period with potential time acceleration are required.

Test planning can be carried out as test to failure and/or as a success run test (see [VDA Vol. 3.2, 2016] Section 7.6). In this case, the test to failure has the advantage that it is possible to obtain the failure probability at a specific load level in addition to making a statement about the minimum reliability. If this is repeated at different load levels, it is also possible to assess the failure probability for different load spectra.

This information is summarized in a matrix that correlates stresses, tests and failure modes. These matrices are already known in various forms (e.g. load test matrix, test relevance matrix, reliability and robustness checklist, load matrix, etc.). Due to the additional details of operating times, time acceleration factors and any defects occurring, it is possible to make a quantitative statement about the reliability of the components and assemblies.

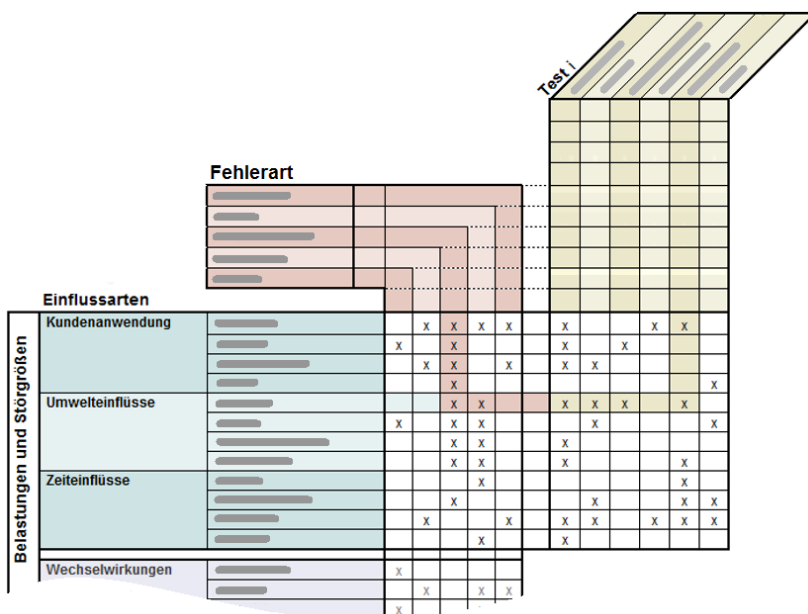


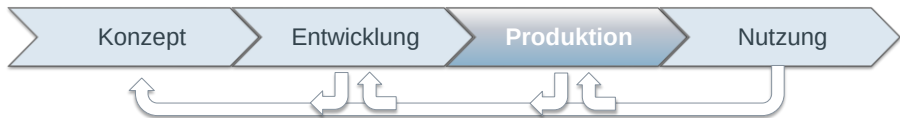
Fig. 2.4: Example of load test matrix according to [Ronniger 2016]

The determined overall reliability (e.g. B_{10} value verified) must be transferred into the key figures of the reliability targets (e.g. failures per vehicle over service life) in order to identify possible deviations early in the use phase. Detailed descriptions for this are given in section 3.2 and 4.2 based on examples.

The verified system reliability has to meet the specified reliability targets, otherwise appropriate measures have to be taken.

The reliability-relevant properties (reliability indicators) have to be transferred as information to the production phase, as characteristics to be monitored within production control plans.

2.2.3 Production phase



The parameters specified in the process FMEA together with the development, including their tolerances for influencing strength, lead to the input parameters for reliability work in production. The specified process quality targets, e.g. ppm, c_{pk} , must be harmonized with the reliability targets depending on service life . As part of process development, limit states (e.g. tolerance samples) have to be considered, using simulations or tests to assess the effect that deviations of the characteristics have on the reliability target in the use phase. In pre-production and also series production, the reliability-relevant characteristics based on the FMEA must be monitored and controlled by means of suitable test methods (e.g. statistical process control, 100% tests, random sample tests). In addition, in-series reliability tests must be planned, specified and performed.

If deviations or abnormalities emerge during monitoring of the characteristics or during the tests, then in addition to initiating immediate

measures based on a root cause analysis process, such as an 8D process, the causes have to be identified and measures derived as well as documented in a suitable data model (see section 2.3).

If the specifications cannot be implemented robustly in terms of production technology, this information has to be reflected to the development phase and has to be analyzed. This information is determined during the production ramp-up phase (focus on industrialization) and from the later root cause analysis in the use phase (focus on concept, development and production errors).

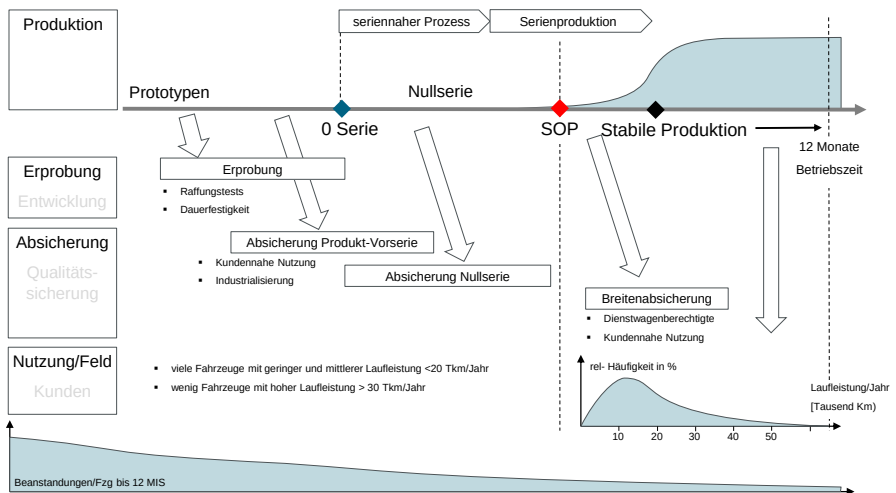


Fig. 2.5: Reliability prediction at the beginning of a new type according to [Jordan 2015]

In this case, it will be determined which characteristics of the components and/or assemblies caused the deviation. The design FMEA and the resulting documents, such as production control plans and process FMEA, have to be adjusted accordingly. If necessary, design modifications can increase the strengths or rule out certain stresses.

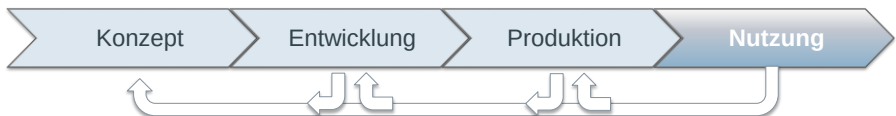
Another possibility may be to adjust the reliability target in the requirements specification or functional specification after consultation with the customer.

However, if a production problem exists, it has to be analyzed and remedied (e.g. modification of the manufacturing process). The effectiveness of the measures has to be demonstrated by reliability tests as part of the production approval process. If no deviations or abnormalities in reliability can be identified in the course of in-series tests, approval for production should be granted based on the previous results and series ramp-up should be started or continued.

During series production, in addition to the statistical process control and the in-process tests, customer-oriented driving tests are also carried out optionally as part of product audits. This provides the possibility of residual lifetime examinations, for example, to compare test and usage conditions. A technical problem analysis has to be carried out if abnormalities occur in relation to system reliability. The causes are identified once more (e.g. 8D process), measures are derived and, if necessary, reflected to the upstream phases (e.g. revise FMEA and reliability targets).

The other process interfaces, such as change management, must be taken into account.

2.2.4 Use phase



As a result of series production, vehicles enter the market which have to be subjected to a field observation. The complaints from the field have to be analyzed after unexpected field failures and potential problems have to be identified. Data from warranty claims and incomplete data of users outside the warranty period can be used for this purpose. In addition, returned damaged parts are to be used to analyze the cause of damage, e.g. from specified return markets. If systematic field failures (deviation from the planned target) have been identified, they must be narrowed down to the vehicles in question and described in detail.

Based on the delimited number of vehicles, it is possible to predict the extent of the field failures, using a Weibull analysis for example. An initial

prediction of expected customer claims may be made without already knowing the exact cause of failure. However, a systematic problem analysis (data with damaged parts) must be triggered which narrows down the root cause, e.g. with regard to a previously unknown stress, production quality fluctuations, workshop problems or a possible combination of these causes.

Using the predicted failures, it is possible to make a projection of the extent of the problem (affected population with failures per vehicle). In addition, measures and their effectiveness (e.g. global 8D process) are specified and tracked in order to reintegrate more detailed information into the phases of the reliability control loop (data model, see section 2.3).

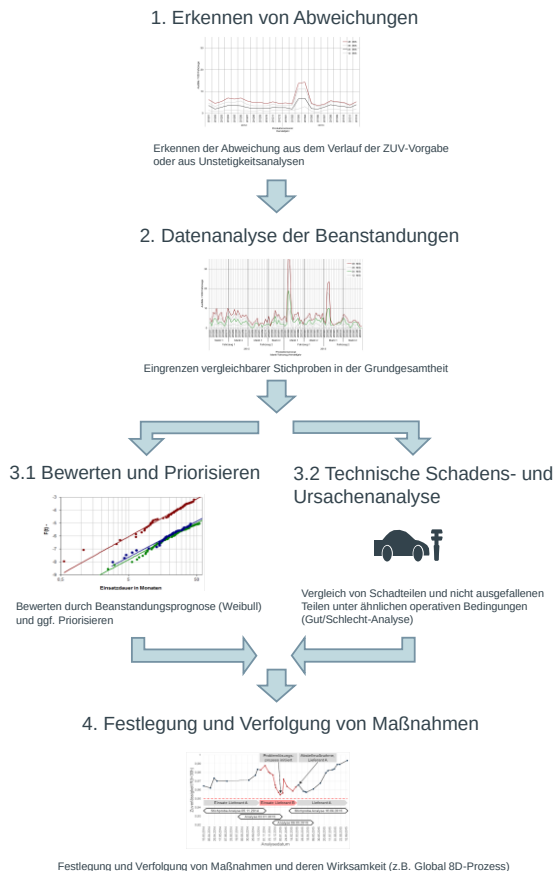


Fig. 2.6: Specifying and tracking measures and their effectiveness (e.g. global 8D process)

2.3 Data standards in the reliability control loop

Assemblies of an individual system (vehicle) lead to complaints if the stresses exceed the tolerable strengths. Stresses result from the usage behavior and environmental factors, they are statistically distributed and can be described by countable characteristics. Strengths result from the technical design, from the production of the components and their quality. They are statistically distributed.

The interaction of stresses actually occurring at a certain time and of the current production quality ultimately determines the frequency of failures (initial failures).

The characteristics describing these failures arising from the stress (use and environment) and strength (production quality) are recorded in a data model, sorted according to assemblies and failure modes. As a result, it is possible to identify key points (stresses and production quality) across vehicles and to reflect them into the production, concept and development phase as empirical values.

Assemblies of a system (vehicle) are developed with assumptions of stresses from the later use phase and tolerable strengths from the production quality to be expected later. Testing and possible failure scenarios emerge from the assumed stresses and strengths. The results on completion of the development are to be considered as an image of the following production and use phase.

The assumed descriptive characteristics of the stress (use and environment) and strength (production quality) are recorded in the data model, sorted according to assemblies and failure modes. As a result, key points identified in the later use phase from the actual stress and production quality can be reflected across vehicles against the assumed characteristics and can be used as empirical values in the production, concept and development phase for current production or later projects.

Assumptions about the stress and strength of assemblies of a system (vehicle) are documented in an image of the later production and use phase and can be represented in one cube model per assembly.

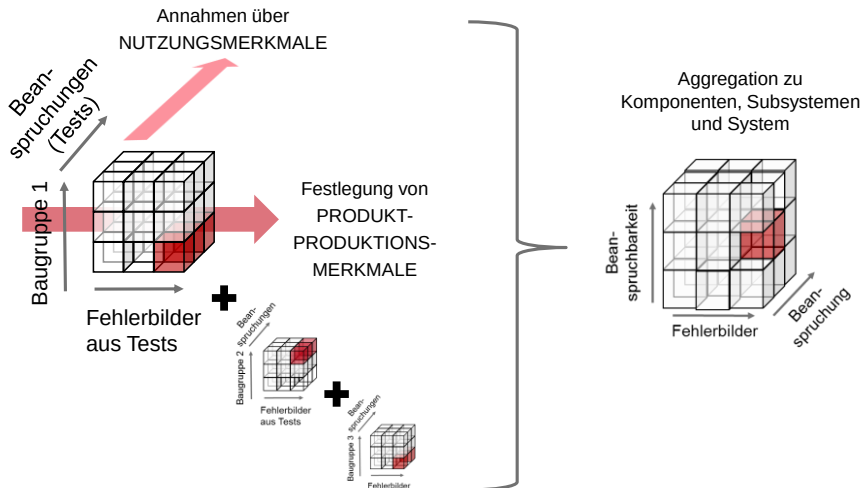


Fig. 2.7: Sketch of the aggregation of assemblies to the component based on a cube model.

The contents are all the described characteristics regarding assumptions of the stress (use spectra, environmental conditions, test scenarios, etc.) and regarding the assumed production quality of the assembly (supplier, OEM). The result of the development is a cumulatively applied curve of the failures expected over lifetime. It also includes a calculable range of variation in which the failures due to actually occurring stresses and the actually achievable production quality might vary.

Actual data on the stress and strength of assemblies of a system (vehicle) are documented from the production phase (supplier, OEM) and the use phase and can be represented in one cube model per assembly; a vehicle is represented aggregated.

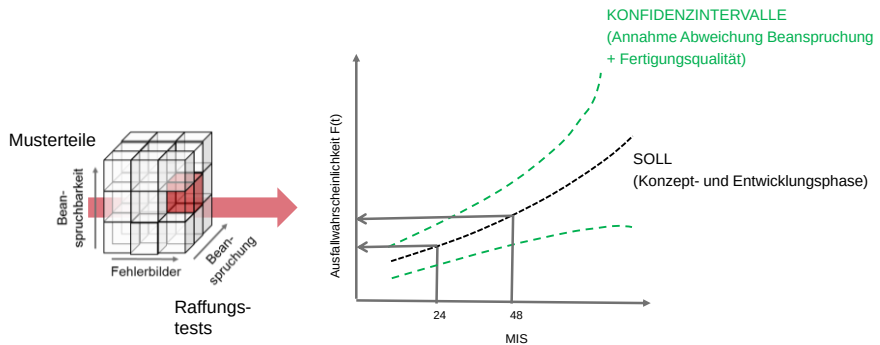


Fig. 2.8: Prediction of the failure behavior from the development phase

If the actual data exceed the calculated range, an analysis will show whether the actually occurring stresses and/or the actually present production qualities cause the deviations.

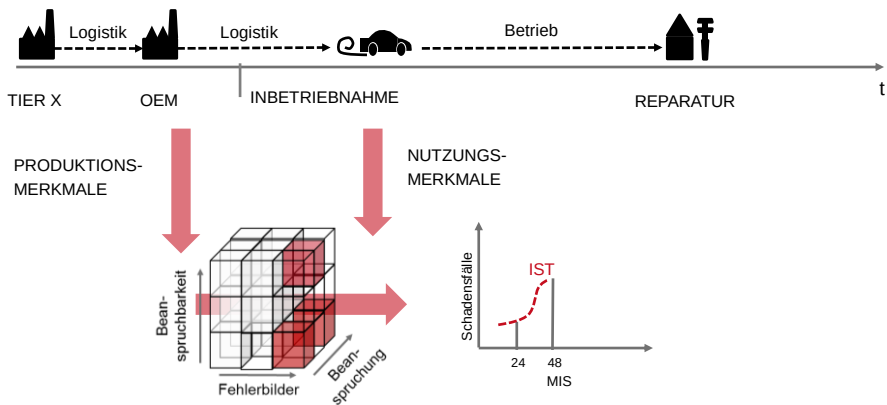


Fig. 2.9: Storage of actual data on stress and strength from the production and use of the system in a productive data model

The productive data model contains all the information about actual stresses (use profile, environment) and strengths (production quality). It is possible to calculate reliability KPIs per produced vehicle from the individual information on the frequencies of failures.

The reliability KPIs per produced vehicle can be tracked and evaluated across the phases (concept, development, production [supplier, OEM], use). Deviations from targets are an indicator for follow-up actions of all the parties involved: Optimization of the production quality (supplier, OEM) and optimization of the component design including test scenarios (supplier, OEM). The development data model supplies the necessary information. It learns from the constant adjustments made by the actual data, the actually achievable production quality and real occurring stresses.

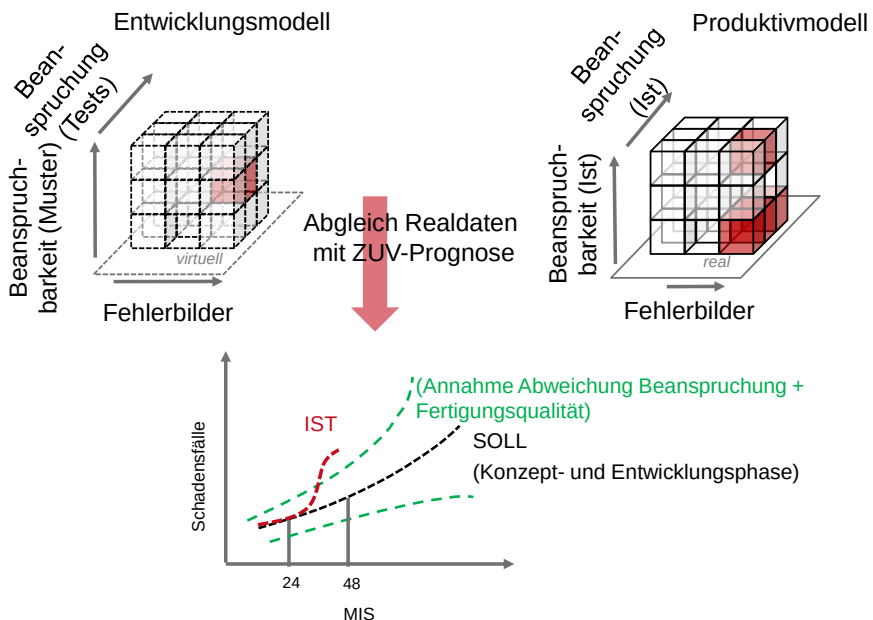


Fig. 2.10: Comparison between target and actual data model

Lifetime reliability planning per vehicle includes all parties involved in influencing their share of reliability with the aim of optimizing the overall

reliability in development and production at the supplier's and OEM's premises by deriving lifetime reliability targets.

Information on deviations in the production quality, stresses from the use profile and environment can be prioritized without much delay in measures for optimizing production (supplier, OEM) or a target-oriented re-design according to user groups or can be used for optimization of the component design (test scenarios) in development (supplier, OEM).

With constant re-adjustment using the actual data, lifetime reliability planning per vehicle in the concept and development phase enables a more accurate prediction of reliability in the use phase.

With knowledge of the actual use, separation into user groups is possible. If the failure scenario expected for these users is known, it allows to develop maintenance or operator models.

3 Example for the reliability control loop: Wheel bearings

This section illustrates the most important questions related to reliability work in each phase based on the example of wheel bearings.

Modern car hub units generally consist of two angular contact ball bearings in an back-to-back arrangement and the mounting flanges for suspension and the wheel, see Fig. 3.1. The angular contact ball bearings have a defined preload due to an orbital riveting process to avoid clearance in operation.

The bearings are filled with a suitable grease to ensure lubrication over the required bearing lifetime. The hub units are sealed to protect against the ingress of dirt or water and to prevent loss of grease. A drive gearing for transmitting the drive torque is additionally required for wheel bearings of driven wheels.

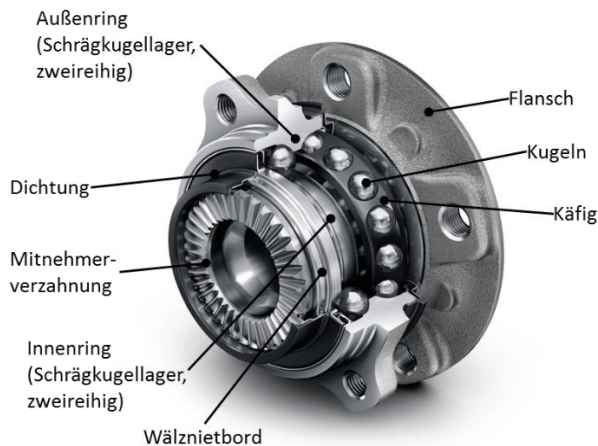


Fig. 3.1: Modern hub unit (image source: Schaeffler)

3.1 Concept phase



3.1.1 General procedure

The reliability targets for a system, in this case a vehicle, are determined in the concept phase. This system can be divided into subsystems, e.g. into bodywork, its mountings, the engine, the transmission, the electrics and the chassis. The wheel bearing is treated as a chassis assembly.

It is basically subject to the same requirements for reliability as the vehicle. The reliability target is therefore shaped by the expectations of customers, the manufacturer, the legal requirements and other expectations, such as environmental friendliness and reputation.

For the purpose of simplification, only the technical and commercial characteristics of reliability are considered here.

With regard to reliability, customers as users of the system only expect a certain number of failures and rate them according to their inconvenience, e.g. repair costs. These expectations depend on the type of use. Customers using utility vehicles may have different expectations than non-commercial customers. The customer's expectations may change as vehicles age. These expectations can be expressed in the key figure "total failures/vehicle over the service life".

From the manufacturer's point of view, fulfillment of the individual user's expectations and evaluation of the quality situation of all vehicles similar to the individual vehicle is paramount. The expectations here are compliance with a quality or reliability target over service life.

Key figures are, for example, the total failures of vehicles from a considered population in relation to all vehicles, depending on their service life or mileage.

Based on the knowledge about the development of key figures over the service life/mileage, estimates can then be made from the manufacturer's

point of view regarding the expected failure rates to vehicle population in use. Thus, the quality level of the vehicles can be calculated more accurately and monitored during the use phase.

From the customer's point of view, these considerations help to estimate how many failures and repair costs might arise per used vehicle after the warranty period. Users may be individual customers or user groups, such as operators or insurance companies.

Fig. 3.2 summarizes and simplifies the manufacturer's and the user's or customer's view of the reliability KPIs.

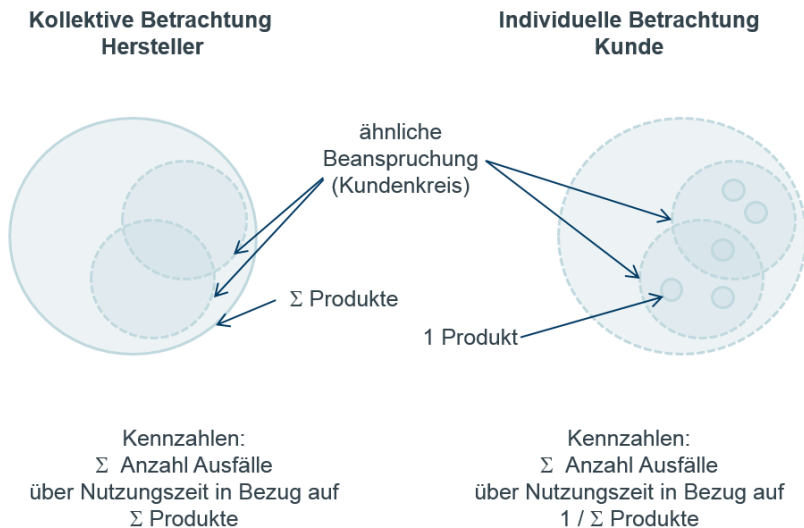


Fig. 3.2: Reliability KPIs from manufacturer's and user's point of view

The user is focused on the individual product, the manufacturer on the total number of all similar products. From the manufacturer's point of view, there are subsets of user groups with different stresses on the vehicles. For example, these may be different climatic conditions under which the vehicles are operated, but also different uses of similar vehicles, e.g. high-mileage driver or standard operation. These differences can be described, for example, by the average mileage per year or month of use.

Fig. 3.3 simplifies the failure behavior of all vehicles with the same wheel bearing type for a population of similar vehicles in standard operation from the manufacturer's point of view.

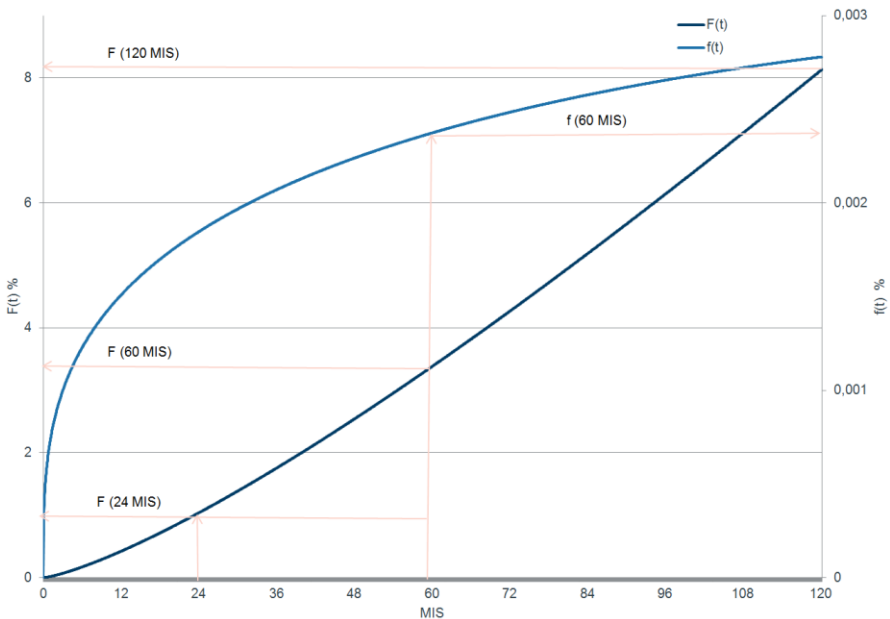


Fig. 3.3: Failure probability $F(t)$ and failure density $f(t)$ over service life

The cumulative failure probability over the service life $F(t)$ or the failure rate shows the likelihood with which a proportion of all vehicles will fail vs. service life. The density $f(t)$ represents the percentage of failures vs. service life (MIS) which all customers of the vehicle population considered here can expect in a given repair period.

In an assumed service life of 10 years approximately 8% of all vehicles may have failed. In the last month, that would be almost one failure, e.g. one wheel bearing or two wheel bearings per vehicle when changing both bearings of an axle simultaneously, for every 1,000 vehicles produced. From the customer's point of view, over a service life of 10 years, the likelihood of a failure would be $8/100 = 8\%$ and accordingly the average vehicle would need to go into the repair shop 0.08 times.

The quality or reliability target can therefore be represented by the function $F(t)$, which shows the quality level of all vehicles of a population over the service life .

$$\sum \text{Failures}(\leq t) / \sum \text{vehicles produced} = F(t) \cdot \text{number of vehicles} \quad (3.1)$$

This results in a KPI which describes the reliability target simply as:

- the number of failures per produced vehicle that is admissible from the customer's and manufacturer's point of view.

In addition, this reliability KPI can be based not only on long-term quality targets but also on interim targets, such as ramp-up quality for example (number of failures per vehicle over 12 MIS).

If a similar element is known from a predecessor vehicle this KPI can be derived in the concept phase based on reliable data from the predecessor product's use phase.

For this purpose, a similar vehicle is considered with a similar component, here a wheel bearing, which is operated under similar conditions of use as the wheel bearing to be conceptualized. The information about failures taken from the warranty data can be used to determine the current reliability or the corresponding KPI. If the predecessor part has already been used for considerable time, complete data may exist for all failures up to the end of the warranty period and may be used to calculate the KPI. Otherwise, extrapolations may be made from incomplete data, see section 3.4.

The chart in Fig. 3.4 shows an example from a predecessor product and the distribution of amounts of this KPI in all failures across all assemblies in the form of a Pareto distribution, based on a service life of 12 months (MIS), as complete data are available.

It can be seen that a small number of assemblies contribute significantly to the total number of failures. As an assembly, the wheel bearing contributes to the occurrence of 80% of all failures per vehicle.

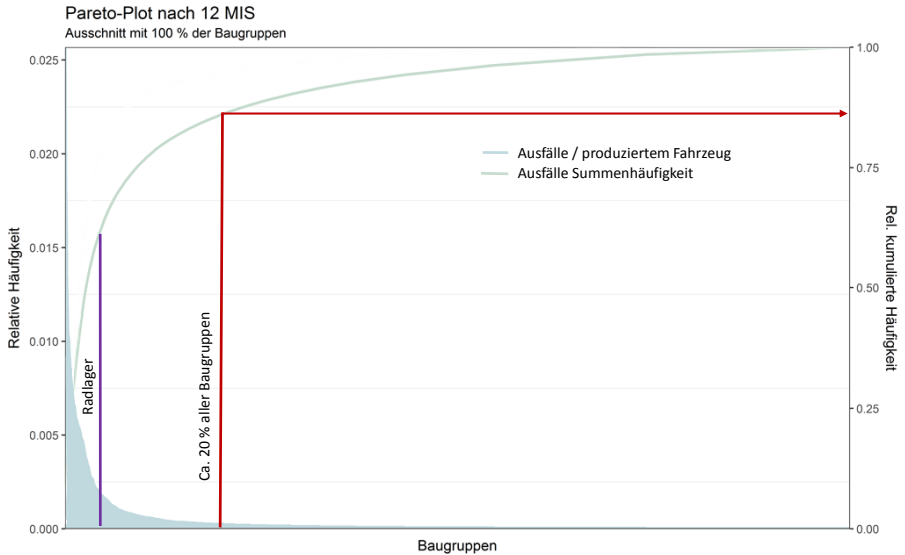


Fig. 3.4: Pareto chart by amounts of failures per vehicle

To classify the aspects, Fig. 3.5 shows the entire structure of the system vehicle to be considered from section 2. The wheel bearing is part of a chassis subsystem.

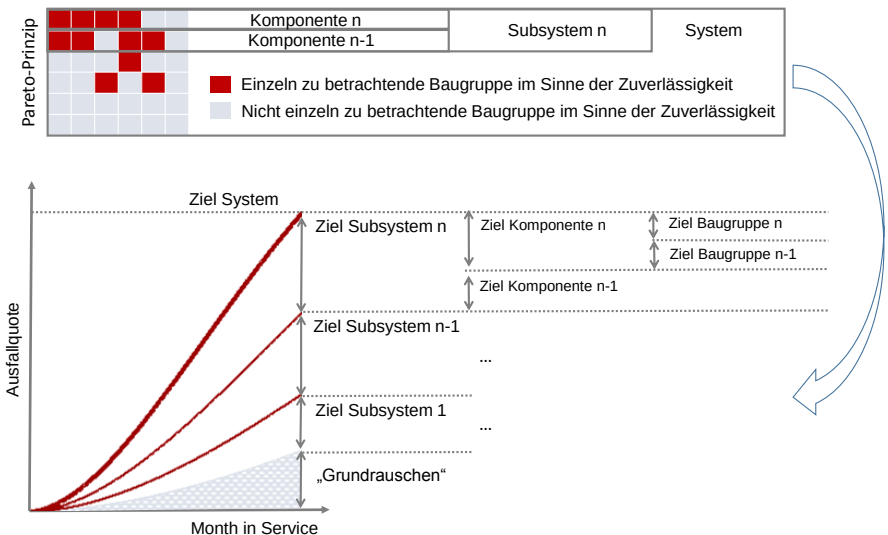


Fig. 3.5: System with assemblies and composition of system reliability target from the assemblies.

The assemblies from the overview of Fig. 3.4 are sorted and prioritized into this general structure. The aim is to specify a reliability target for the entire system (vehicle) and also for all its assemblies over the service life. Obvious criterion is the cumulative failure probability $F(t)$ of the predecessor model, either from the actual data existing such as from a completely fulfilled warranty period or from a prediction about the failure rates to be expected over the service life. Other criteria, such as laws to be complied with, are incorporated via the design FMEA. Derivation of the reliability targets over the entire service life using the information from the warranty period can only represent an initial assumption. This is because the warranty period only represents a small proportion of the total useful life and the failure behavior of the assembly outside this period can be significantly influenced by different behavior. For example, in certain assemblies, early failures and/or random failures can occur in the first 12 months of use, after that mainly initial wear is found. These considerations show the importance of monitoring the longest possible service life of predecessor products to obtain clues about the failure behavior for longer periods of use. In some assemblies, wear can start until well outside the warranty period. Here, corrosion is a typical failure mechanism. In this case, it is not possible to draw conclusions about the failure behavior to be expected from the first known period of use. A design FMEA with a systematic exploration of possible failures under certain stresses and the use of data from similar known assemblies, also taking bench or road test results into consideration, can be helpful.

In this example of the wheel bearing, few failures with wear failure behavior are already known from the later warranty period of the predecessor product. This is shown by the analysis of corresponding data from the use phase, see Fig. 3.8. Placement of the wheel bearing in the high risk area of the Pareto chart, marked by the blue line (Fig. 3.4), additionally ensures that this assembly is specified as one to be considered separately. Other assemblies from the area with significantly lower failure rates, which can not be assigned easily, have to be considered separately. For example, if safety and/or legal requirements have to be fulfilled. The previous observations are based on restricted and therefore incomplete information and have to be adjusted to the planned level and extrapolated:

1. The vehicle and the assembly are only similar.

Derived from strategic considerations, the reliability target to be specified can be reduced and specified by deducting x% from the known reliability target of the predecessor product. The planned use of a technically higher value product, just like a more complicated product with new parts not previously used in the assembly, can affect the planned reliability target by decreasing or increasing the risk. As an example, an actual reliability of the predecessor decreases from 0.01 failures per vehicle to a reliability target of 0.0095 failures per vehicle for the new assembly up to 24 MIS. Similarly, the reliability target for 48 MIS decreases from 0.025 failures per vehicle to 0.02 failures per vehicle.

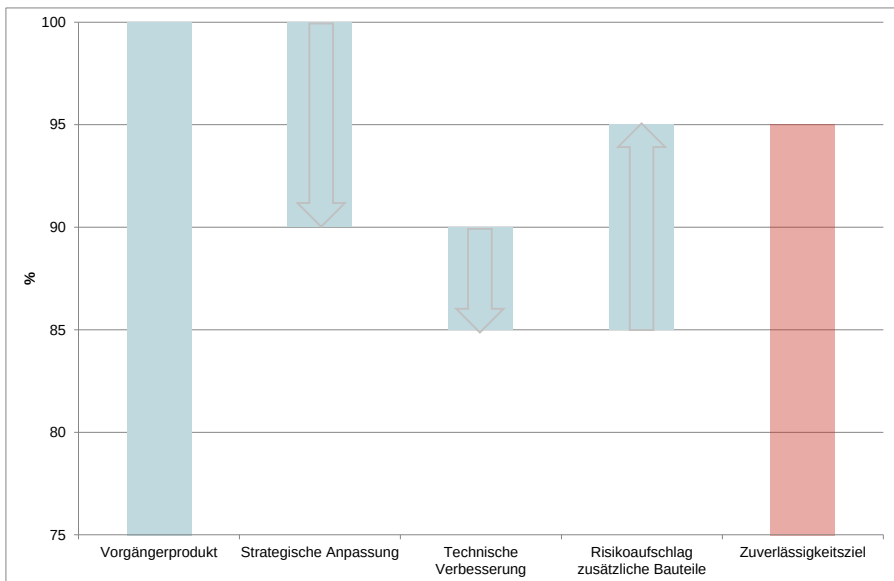


Fig. 3.6: Adjustment of the reliability target

2. The production period has quality variations.

It is necessary to analyze variations in the production quality and to estimate whether it is possible to ensure that the deviations can be minimized in the case of a planned use in future. Fig. 3.7 shows an isochronous diagram for a wheel bearing with two clearly different levels of

quality as a function of the production periods. The target is to ensure consistently good production quality from the more recent period.

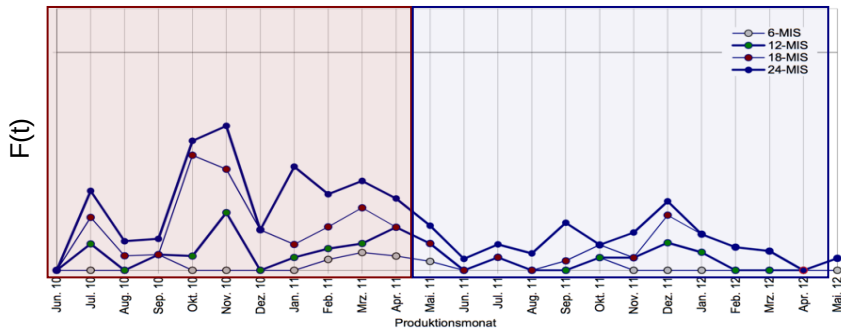


Fig. 3.7: Isochronous diagram based on the example of a wheel bearing

3. The period of use is incomplete (warranty period).

The data analysis from the warranty period can be used to extrapolate the achievable reliability target outside this period. It can be assumed that the failure behavior identified with a Weibull analysis is also valid outside the warranty period. Fig. 3.8 shows such an extrapolation as an example. This assumption can only be made if a plausibility check of the failure behavior is set up with technical analyses of the damaged parts.

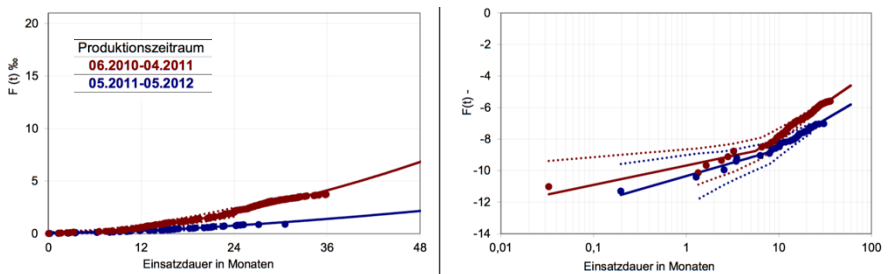


Fig. 3.8: Extrapolation of the failure behavior by Weibull analysis (example)

4. The stress on the assemblies and the resulting failure behavior originate from the use of the predecessor product.

Different groups of individual stresses, which are made up of market-specific characteristics, such as climatic or traffic-related peculiarities (e.g.

cold, heat, dust, road density and type), or are characterized by the use behavior of different customer groups (e.g. high-mileage drivers or standard customers), can be grouped together in the overall stress. These stresses have to be analyzed for future use. They have to be taken into account which of them will remain and which effect they will have on the overall failure behavior. Additional stresses might occur because of new markets or new user groups which were not present in the predecessors product.

Furthermore, they may differ between various user groups (e.g. high-mileage drivers/standard drivers).

The following example shows the effects of using similar vehicles with stress due to different user groups for manufacturer and user groups.

3.1.2 Specification of reliability targets based on wheel bearings example

New system, specification of reliability targets for system and subsystems

A new vehicle project was agreed. In the following, the vehicle will still be considered as “system”. The desired reliability target for this system has already been specified in advance. It describes the accepted number of claims per 100 vehicles over the service life. Sub-targets are derived for subsystems, such as the front axle, and also for their lower-level components and assemblies. In this case the wheel bearing is an element of the front axle.

Identify critical assemblies/components

The frequency of wheel bearing complaints is especially noticeable when analyzing assemblies that particularly stand out in the predecessor series (see Fig. 3.4). Furthermore, it is assumed that in future the new vehicle will be used to a greater extent as a high-mileage driver, e.g. taxis (increase in mileage km/year). The increased mileage per year leads to increased failures of the wheel bearing if the failure mechanism is dependent on mileage. Since the wheel bearing is designed for a certain mileage, this increased use tends to result in increased number of failures. In this case,