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EARLY RELIABILITY ESTIMATION IN AUTOMOTIVE INDUSTRY

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ABSTRACT
Increasing functional requirements and system complexity on the one hand, and decreasing time for development as well as cost reduction on the other, are some of the challenging constraints that car manufacturers face today. Additionally, customers expect high quality products. To meet these challenges, a quantitative reliability estimation method that can be connected with established methods is necessary, even in early development phases.
The present paper illustrates a method for early quantitative reliability prediction of mechatronic systems such as in automotive engineering. The core of this method is to support a reliability-oriented system development based on quantitative failure rates. It combines a functional system analysis and quantitative data in an integrated approach. Ultimately, criticality analysis and reliability optimization are facilitated.
To demonstrate the features of the method, a typical automotive system of a car power-window regulator is illustrated.

Keywords: reliability, reliability prediction, reliability modeling, automotive systems

1 INTRODUCTION AND REQUIREMENTS
According to recent studies, reliability has always been among the top criteria when purchasing a new car. This holds for worldwide customers as well as for the German market [1, 2]. For this reason, it is inevitable for car manufacturers to develop and produce high quality cars. At the same time, the development of a new car becomes more and more complex. An important factor for that is the increasing number of functions in order to make cars even safer and easier to use than they are nowadays. Examples for complex functions are driver assistance systems such as adaptive cruise control, night vision, and advanced protection of pedestrians. These two aspects, high quality on the one hand and complex systems on the other hand, must be regarded throughout the whole design and production cycle of new cars.
In order to cope with that challenge, manufacturers put an enormous amount of effort into their quality management, especially those that deal with premium passenger cars or commercial vehicles. One important part of that quality management is the reliability analysis. Goals of the reliability analysis are to find and remove possible weak spots as well as to quantify the overall reliability. The analysis typically ranges from qualitative methods in early design phases, such as the failure mode and effects analysis, to quantitative methods in later phases [3]. In order to quantify the reliability, empirical data is required and has to be evaluated by using statistical methods [4]. Car manufacturers, as well as their suppliers, usually have large databases with empirical data stemming from component tests, test drives, and from field operations, cf. [5]. Quantitative methods based on such databases allow a detailed analysis of components and systems with respect to reliability.
In spite of these quantitative methods for the test and operation phase, there is still a need to quantify reliability in early development phases in a manageable way and integrate this analysis with the already established methods. At that time, engineers still have possibilities to change design parameters or certain functionalities. However, if these decisions turn out to be wrong later in the development process, corrections will require a lot of money and time. This relation is known as the “Rule of Ten” (Figure 1).

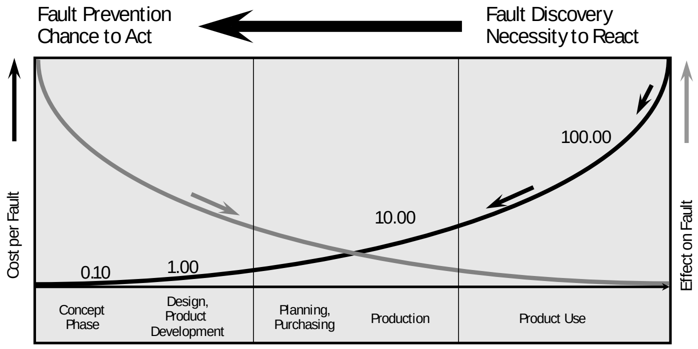

Figure 1: The Rule of Ten

Based on these considerations, a quantitative method is required in order to verify a design concept and to ensure that the system meets a given reliability goal. Such a method has to fulfill the following requirements:

- **Verification of reliability target:** the whole system often has to reach a certain reliability goal, which is given by management or customers. The method has to demonstrate that the system will meet the goal. If the goal cannot be reached, the method has to point out the shortfalls.
- **Identification and quantification of weak spots**: critical components, which either have a high impact on the system reliability or possess a very low reliability, have to be identified. How many single components have to be improved in order to meet a given reliability target has to be quantified.
- **Derived recommendations for testing**: the method has to give advice for the downstream testing experts. Already knowing where to put the test focus and which failures can be expected in which time frame can be a great advantage.
- **Method integration**: the early reliability prediction must integrate with other new and established quality management methods. On the one hand, these are methods in early phases, such as a concept selection based on qualitative criteria. On the other hand, these are quantitative methods in later phases. Typical methods in the automotive domain are the failure mode and effects analysis (FMEA), fault tree analysis (FTA), and design for six sigma (DFSS).
- **Application in the automotive industry:** the method has to be efficient and must not cause too much overhead for design engineers during the early development. It must also define precise guidelines, how to organize workshops, and which questions to ask in order to retrieve the required empirical information.

A method that fulfils the listed requirements has to cope with several challenges at the same time. These challenges arise from the prediction in early development phases, the consideration of mechatronic systems, and the application in the automotive industry.

A major problem in **early development phases** is the lack of precise empirical information about component and system failures. Either this information is completely missing or it is subject to uncertainties. Furthermore, the type of information and its possible variations can be completely different among components used for a concept. For example, design engineers might have expert knowledge concerning a particular component with which they are familiar. In this case, they are able to give an expected reliability range and to quantify how likely it is that this range will be reached. Other examples are handbook data or field data from similar components in comparable systems. In this case, the data must be transferred to the current system.

Another challenge results from the **consideration of mechatronic systems**. These systems are built up from mechanical, electronic, and software components, which are partly constructed by the automotive manufacturer, and partly delivered by suppliers. While mechanical and standardized electronic components fail due to physical and chemical mechanisms, individual electronic and software components fail due to logic faults. In spite of these different failure mechanisms, all types of components have to be integrated into an overall prediction of system reliability.

The third challenge is the **integration of a quantitative method into an existing infrastructure** within the automotive industry. This means that the method has to use existing data interfaces and must use information from other already established quality management methods.

According to an analysis of existing methods, no integrated and systematic approach currently exists that fulfills the given requirements and challenges in an industrial environment. The most important issues are the early retrieval of empirical information, the use of expert knowledge, and the integration of predecessor data. Because of this, a new method that takes these issues into account was developed in cooperation with a major industrial automotive partner. This was done by applying an initial idea of the method on several pilot projects. In doing so, the method was adjusted systematically to the engineers' needs and company's requirements.
The following section describes this method in detail. After that, section three gives an example of how the method is currently applied.

2 METHOD FOR THE EARLY RELIABILITY ESTIMATION

As given by the requirements, the method is embedded into the given industrial environment. Already standardized methods for the automotive industry, such as FMEA, analyze a system in early development phases on functional and structural levels. For example, function and component structures are results of an FMEA. The early reliability prediction, as described in the following, also requires this input information. Hence, in order to avoid unnecessary additional effort, the information has to either be reused from other methods or created as part of the reliability prediction, and then provided for further analyses. This import/export relation is depicted in Figure 2, which shows how the reliability prediction is embedded into the existing environment.
The phases one (System Description and Modeling), and two (Reliability Modeling), interface with other quality and reliability management methods. In particular, they support qualitative methods such as FMEA or proprietary concept selection methods. The latter is a novel approach to compare the feasibility of concepts according to qualitative criteria, which is further described in [6]. In phase three (Data Collection and Analysis), data of system components must be collected and systematically analyzed with respect to their reliability. Thus, this phase must both interface with existing quality databases and interpret expert knowledge concerning the system under analysis.
Finally, in phase four (Reliability Analysis), the collected data is collected into an overall reliability estimation by using the reliability model from the second phase. The initial prediction with its associated reliability model can be used throughout the following development process for reliability simulation. As soon as more data is available, such as from tests of the actual components, the estimation is refined. The following paragraphs describe how weak spots can be identified based on this prediction. There, all four subsequent phases are explained in detail with their inputs and outputs.

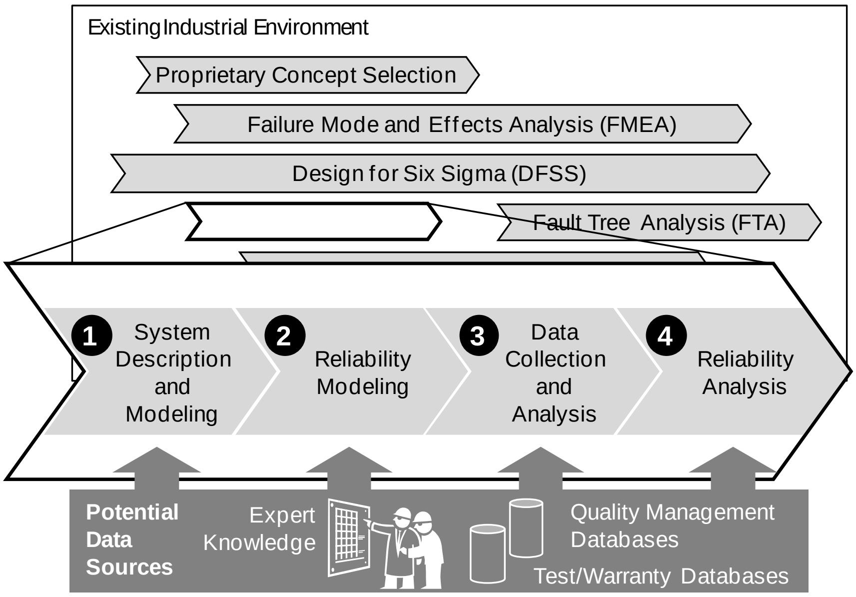

Figure 2: Early reliability prediction method embedded into the industrial environment

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The first phase, "**System Description and Modeling**", contains a systematic analysis of the functions performed by the system and leads to its functional structure. Furthermore, all necessary components

have to be identified and the relations between possible malfunctions and the components involved have to be detected (Figure 3).

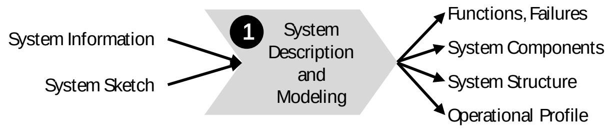

Figure 3: Phase 1 - System Description and Modeling

The following phase, "**Reliability Modeling**", aims at drawing the system's reliability structure to demonstrate the reliability relevant relations between the components (see [7] and [8] for suggestions on the derivation from early functional models). To handle the special requirements of complex mechatronic products, the fault tree model is used. To support a reliability-oriented system development, a reliability goal is needed for the whole system. It either is provided by management or can be estimated by the engineers. Safety-critical functions are documented as well, but will not be used further because special methods exist for this purpose (Figure 4).

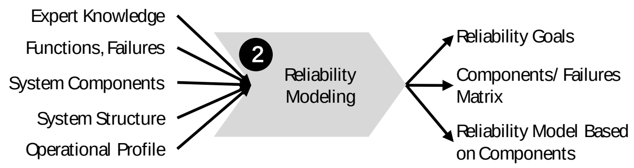

Figure 4: Phase 2 - Reliability Modeling

To quantify the system's reliability structure, any reliability-relevant **data** has to be **collected** and **analyzed**. Even if there is little information about the current system development, many sources exist with usable reliability information, such as in-house databases (e.g. databases with warranty/field/operating information), expert knowledge, information about predecessors or similar systems or supplier information (cf. [9]). Therefore, systematic analogy verification is carried out and the comparability of component and load characteristics is checked. Using the huge body of expert knowledge, quantitative reliability data can also be estimated for new and innovative components. Using and combining all relevant data sources, each component is linked with the information found (Figure 5).

Figure 5: Phase 3 - Data Collection and Analysis

In the fourth phase, the "**Reliability Analysis"** is executed which gives a detailed view of the system performance relating to reliability (Figure 6). It offers different ways to analyze and compare system reliability:

- summed-up bar chart of failure rates for each system component:
  - presenting the total estimated reliability
  - checking the compliance with the defined reliability target value
- main influencing components: identification of components with the most influence on system reliability and developing proposals for how the components should be treated in further development and testing phases
- criticality analysis: identification of critical system structures and paths, derivation of proposals for improving the reliability of the system
- optimization: analyzing and offering optimization proposals for increasing the reliability of the system

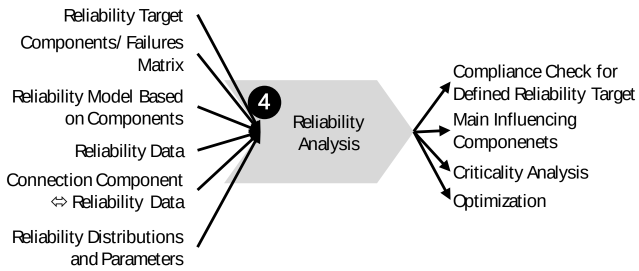

Figure 6: Phase 4 - Reliability Analysis

Even if there is only partial quantitative reliability information available for the new system, the reliability analysis allows an assessment of the system's concept concerning reliability. Regarding the main influencing components, the method enables a criticality analysis to be performed and a derivation of optimization proposals to improve the reliability of the system. Furthermore, the definition of functional reliability target values allows ensuring the development of a reliable and trustworthy system. The next section will show how this method is currently applied.

3 METHOD APPLICATION IN AN AUTOMOTIVE COMPANY

Currently, this method is applied in several projects where the reliability of novel systems is quantified. Typically, the system concepts are in a very early stage. Each step of the method is conducted in workshops together with engineers familiar with the system details and quality management experts. The engineers cover all departments involved, ranging from construction over calculation to production. In order to complete all steps of the method, an average of five workshops of two hours is required. This shows the low additional effort for the engineers. Additionally, they can save time when transferring the results to other methods. To demonstrate the application of this new method, a simple system of a car power-window regulator is used.

In the first step of the method, the system functions and the components of the system have to be identified. The analysis results in two general functions (open automatically, close automatically) and one safety-critical function (retract if blocked). For each function, potential failures or malfunctions are derived as shown in Figure 7. This is done with a structured analysis, where each function is combined with keywords for failures, such as "not", "just partly" or "unintentional".

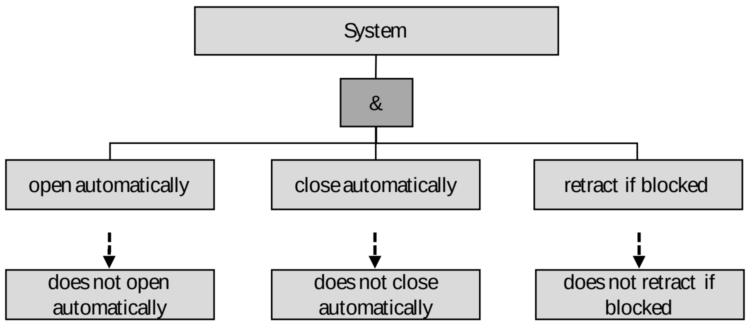

Figure 7: From the function tree of a Car Power Window Regulator, malfunctions can be deduced

Next, the components of the system have to be listed. The system is a double-rail drum and cable window regulator consisting of the following components: left and right guide rail, upper and lower left and right roller-type guide member, left and right carrier unit, drum, electric motor, cable wire, control unit, wiring, and other less important components not regarded in this case study, Figure 8.

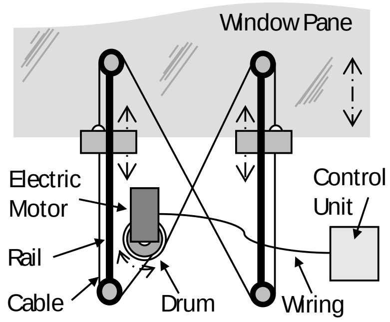

Figure 8: Sketch of a double-rail drum and cable window regulator

At the beginning of the second step, reliability targets for each malfunction are defined by expert estimation. If the system's planned lifetime is to be 'x' years, the reliability target is given as 'y' workshop visits per 'x' years. This information is obtained for each malfunction, as well as once for the entire system. With the reliability target for the entire system, the single targets of the malfunctions, which are mostly overestimated, are then normalized. After that, a fault tree is created in order to assign component failures to malfunctions. When the system components and the system structure are complete, they have to be matched together. This happens by dint of a matrix, which shows the connection between component failures and malfunctions. For each malfunction, all components whose failure could lead to the malfunction are marked. It is now possible to complete the fault tree with the basic elements – the component failures.
It is then determined that the system contains no redundant components and, hence, consists of a series reliability structure. The resulting fault tree is shown in Figure 9. The failure of one component leads directly to a system failure. This is a very common situation in the automotive industry because low weight and costs are very important boundary conditions.

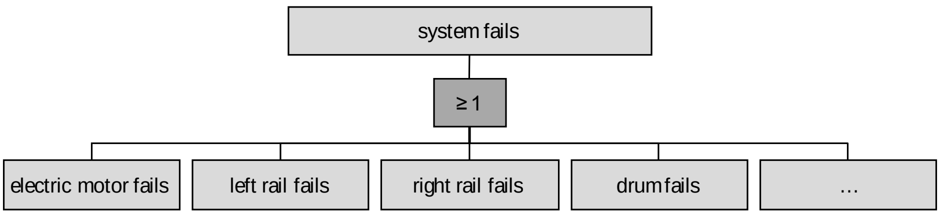

Figure 9: Fault tree combining component failures to system failure

This has the consequence that the overall reliability of the system

$$R_{System} = \prod_{i} R_{Component,i} \tag{1}$$

is the direct product of the components' reliability.

In the third step, reliability information is investigated. A similar system has already been used in the predecessor vehicle, but the new one contains a new-generation electrical motor that also requires adapted control unit software. In-house field data for the predecessor power regulator is available, but only for the old electric motor and control unit. Nevertheless, the electric motor and the control unit are similar to the ones of a predecessor power sunroof, so their failure data can be used for at least a rough estimation. This consideration was also verified in cooperation with the development experts of the supplier, who confirmed that the assumed reliability value of the newly developed electric motor is realistic.
The available in-house field data contain the number of defect components in relation to running components, which leads to the failure rate. Because software failures were not recorded separately, the failure rates for the control unit contain the mechanical failures as well as the software failures. However, this is no disadvantage, because the newly developed control unit also contains mechanics and a precise splitting between domains is not necessary.
In order to avoid the engineers not relying on the quantitative results, the final decision for a component's failure rate is theirs. The given failure rate from predecessors or literature is always just a

recommendation. The experts have to decide - based upon the given data - which failure rate to enter in the form. This allows them to adjust the documented failure rate slightly, and to set their own priorities among the components. The decisions have to be documented with an explanation.

Finally, in the fourth and last step, the results are assessed. The failure rates of all components are summed up and compared to the reliability target (see Figure 10). A simple summarization is only possible in this case, because the system consists of a purely serial reliability structure and the reliability distribution of field data assumes an exponential distribution. Thus, the overall failure rate is a simple addition of each component's failure rate and a direct measurement of the system's reliability.
The clearly arranged bar chart shows that the system narrowly exceeds the given reliability target. It also shows the most critical components, with the highest failure rate being most obvious. This makes it possible to put further focus on them. In the example, the most critical components are the upper and lower roller-type guide members, which seem to be weakly dimensioned. Consequently, further preventive analyses can be done early on these two components - ideally in a design to make the guide members more robust. This is the most important advantage because, in the early stage of development process, there is still time to change the product design or to adapt the requirements for suppliers.

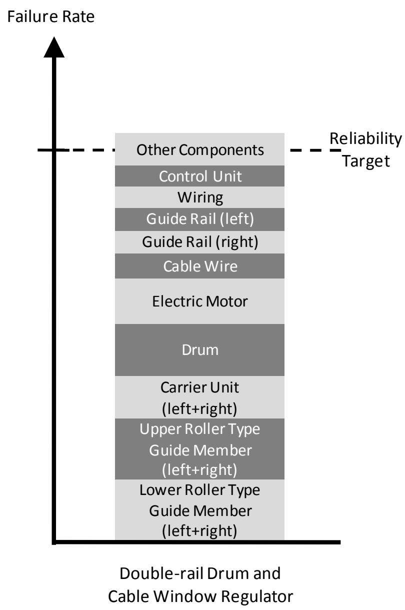

Figure 10: Failure rates summed up and compared to the reliability target

Another consequence of the apparently weak roller-type guide members could be a special testing program in order to verify that the guide members fit the loads of the new car power-window regulator.
The prioritisation of test runs based upon the failure rates is just one advantage: another advantage is a better base for planning the test runs. If it is known how long it will take to get a component failure, it is easier to calculate the test duration and sample size. Quantitative reliability data can be used not only for internal needs; it can also be used in the requirement specification as target value for suppliers.
For the reliability optimization and the criticality analysis, expert knowledge is being used mainly in an implicit way. When the engineers discuss the reliability performance of their systems' components, they are faced with the failure modes of the predecessor components. At the same time, they check the new components for the same issues and normally they have several suggestions for improvement. At this time, the quantitative-oriented method becomes qualitative because of the improvement suggestions. These suggestions can be analyzed upon realisation or increase in reliability. And because all of this happens early in the development process, the suggestions still can influence the design of system.

Finally, the engineers have a comprehensive documentation of their system's expected reliability including notes on comparable systems and their failures. Because each single decision was well documented, a later update of the analysis is possible, e.g. with new roller type guide members.

4 EXPERIENCES AND SUMMARY

As a result, the method fulfilled the requirements stated in the first section. It proved to bridge the gap between detailed and theoretical methods on the one hand and the everyday challenges of an engineer on the other hand. By collecting available data from different sources such as expert knowledge and in-house databases with warranty data, the reliability of the basic components was identified in a manageable way. Then, the reliability could be combined based on their contribution to system functions. This resulted in an absolute quantification of the system's failure rate. In addition, critical components could be identified and suggestions could be made as to how these components should be treated during further development. Possible outcomes were: the intensive testing of a component later on, the need to improve the reliability of components, or the confirmation that the required reliability will be reached with the given set of components. Finally, the integration of other quality management methods was successful: for example, information about function, failure function, and components could be imported from other qualitative reliability methods.

Another possibility is to perform the analysis repeatedly during the product development. There can be a rough reliability estimation at first, which will then gets refined iterative with the time.

In summary, this method supports engineers in quickly retrieving, structuring, and using reliability information that is already available in early development phases. By applying the method, reliability can be predicted early in the development process. The presented method also helps get a better understanding of the system's behavior and its critical components. This not only supports the reliability-oriented development, but also helps to turn the engineers' attention to components that are crucial for system reliability.

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