Robustness of Inventive Design Solutions - Transferring the Robust Design Focus from Production Process to Development Process

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Abstract

Conventional Robust Design methodologies consider deviations of product parameters during production and use. While it is acknowledged to integrate Robust Design methodologies as early as possible into the product development, most approaches neglect the systematic consideration of uncertainty due to the development process itself. This leads to a major drawback for inventive design solutions, especially within highly standardized and rapid development processes like car development. The proposed solution overcomes the major obstacles for the application of Robust Design in early design stages by identifying all relevant types of uncertainty. Furthermore, methods for the evaluation of robustness against uncertainty are shown. Finally, an optimization process is proposed and verified using an automotive example.

Keywords:
Early Design Stage, Robust Design, Inventive Design

1 INTRODUCTION

Current car development is focused on building modularized cars assembled by a certain amount of modules. Ideally, companies define one technical standard solution for each module, the standard module. This standard module has to be capable of being integrated into the highly standardized and rapid development of every new car project of the whole company. The development of the standard module solution needs to take place in the first design stages. The influence of uncertainties of the development process itself dominates decisions in early design stages. Therefore, one major issue of module development is the question which possible solution is best capable of handling deviations from the car development process. Currently, no method is established in module based development to systematically handle uncertainty. Therefore, the decision about the standard module is based on estimations instead of calculations. Consequently, conventional and approved solutions are usually favored in industries with highly standardized development processes. This leads to a major disadvantage for unconventional solutions possibly found by inventive design methodologies.

The aim of this paper is closing the gap between inventive design solutions and their integration into development processes based on the module paradigm.

1.1 Inventive Design Solutions

At the beginning of a module development, developers strive to obtain the maximum number of solutions possible. Therefore, both conventional and inventive development methods like TRIZ [1] are usually taken into account. Recent research activities in the field of Computer-Aided Innovation (CAI) intensively investigated the question of how to systematically come to innovative or inventive products by methods or tools [2]. The increasing applicability of methods like TRIZ enables developers of automotive modules to reach a higher level of inventiveness during the very first stages of car development. However, the demanding functional requirements of the automotive industry and tough timing combined with the high sensitivity for uncertainties during the development process lead to problems of acceptance of such tools. As a consequence, designers tend to fall back to proven and tested conventional modules. It can be concluded that innovative or inventive solutions based on CAI methods only will be considered in early stages of module development, if they sufficiently account for uncertainties that arise during later stages of the car development process.

1.2 Challenges of early design stage

The automotive development process is structured into the phases ‘strategic development’, ‘preliminary development’ and ‘mass-production development’. Due to increasing variety of future product portfolios, the need to use more standardized modules is inevitable. This means that a vehicle is assembled by a certain amount of modules. The module paradigm aims at the comprehensive standardization of every module within an OEM. Thus, the standard modules are adapted specifically for each car project. This eventually leads to reduced costs because of scaling effects.

The development of standard modules requires very early evidence about the fulfillment of functional requirements in very different car concepts. Standards for modules are developed within the strategic development phase. Later development stages focus on the integration of those modules into the assembled product.

Uncertainties are present during every stage of product development including production and use of the final product, see Figure 1. Typically, large uncertainties are present at the beginning of the car development process and decrease over the timetable reaching their minimum after the ramp up of the mass production. Once a product reaches the area of unreliability in use, uncertainty in terms of probability of failure increases again.

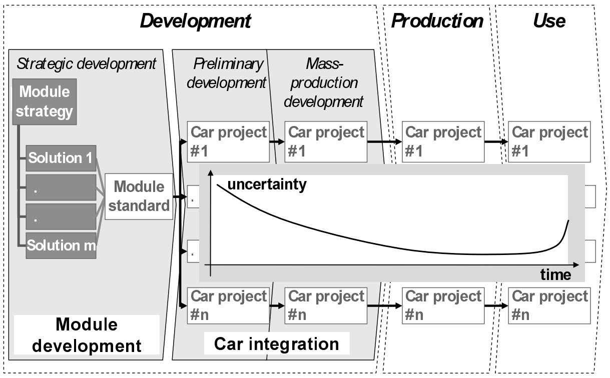

Figure 1: Uncertainty during standard module development and car integration

As shown in Figure 1, the decision about the standard module has to be done very early and influenced by the highest level of uncertainty possible. The neglect of those uncertainties within the development of a standard module typically leads to high changing costs during the car integration phases. Furthermore, the consolidation of different solutions for standard modules likely results in proved solutions because designers have no method to handle the uncertainties influencing innovative solutions during car development.

Therefore, a new approach is needed. This approach focuses on identifying the most robust concept for standard modules taking into account the high amount of uncertainty during the development process.

2 ROBUSTNESS IN EARLY DESIGN STAGES

The targets mentioned above can be translated into an extended application of robust design methodologies. A brief summary of the progress of robust design approach from design paradigm to probabilistic based simulation method builds the fundamentals for introducing the new approach of early optimization of robustness.

2.1 Design to Robustness

Taguchi's idea of minimizing processes and use deviations of a product during its development caused a fundamental change in quality improvement methods [3]. Based on the international acknowledgment of Taguchi's paradigm, further works introduced Design for Six Sigma (DFSS) [4-5]. DFSS methods aim at systematically reducing the level of failure probability to a level of 4.5 σ or higher during the development of a product. Hence, the ideal of a 'zero defect' production is sought starting in the early design stages.

Within this framework, description methods like the P-Diagram were developed. A P-Diagram interprets a product as an input/output system with signal, noise and control factors influencing the product's output. In early design stages, P-Diagrams are appreciated as a demonstrative way to gather noise and its impact on the product [6].

Nee [7] interpreted a main potential of the Taguchi approach in identifying significant design factors prior to optimization. Gu [8] later combined the robust design paradigm with Axiomatic Design. This extension of engineering design transparently enables the assessment of an analyzed product design in comparison to its robust and ideal design. An ideal design is characterized by independence between uncertainties and functional features of the product. A robust design represents minimal influence of uncertainties on functional features.

Product designs can be changed easiest during the first stages of development. Because decisions about conceptual designs typically have to be done under a high level of uncertainty, Gheorghe [9] developed methods to aid concept decisions with the problem of high fuzziness during early design stages against the performance and profit of the final product.

Uncertainties are often equated with the complexity of early concept decisions. Because interactions and interdependencies between product features and noise factors are initially unknown, works like [10] seek to analyze concept interdependencies including all areas of product development (e.g. product functions, production concepts).

All in all, it can be concluded that Robust Design methodologies aim at characterizing and identifying the dependencies of different factors determining product behavior during early design stages. Based upon statistical analyzes, developers are able to identify deficits in order to design robust products.

2.2 Simulation based optimization to Robustness

Due to significantly decreasing costs for computer calculation power over the past years, robust design approaches extended from design paradigms to simulation methods. Latest developments enhance the robustness analysis by adding optimization algorithms. In mathematics, Robust Optimization (RO) covers the optimization of systems under uncertainty [11].

The probabilistic variant of the RO approach typically focuses on production issues by optimizing designs (e.g. topology optimization) while considering product scattering during production and use in parallel [12]. The goal is to investigate and optimize designs in order to maximize reliability of products to the area of six sigma.

Unlike analytic RO in mathematics, the optimization process of probabilistic RO is dominated by stochastic artificial life science algorithms. Based on examples like evolutionary or genetic optimization, research works like Roy [13] demonstrated powerful extension possibilities by integrating uncertainty not only into design variables but also into decision criteria. Applications like Zhang [14] showed that even the tolerance specification of design parameters can be optimized simultaneously by using the probabilistic RO approach.

2.3 Summary

All presented forms and enhancements of the robust design approach have one aspect in common. A product is designed and optimized to be robust against uncertainties of the production and use processes. In the future car development aims to have cars assembled by standard modules exclusively. Standard modules need to be developed in very early design stages. Later in the car development process, these standard modules must be capable to handle the uncertainties caused by their integration into distinct vehicles. Currently, no method is available to handle uncertainties during car integration. On the one hand, this results in suboptimal performance of conventional standard modules. On the other hand, developers tend to avoid inventive solutions for standard modules because uncertainties for novel solutions are even larger. As future car development will be heavily affected by the module paradigm, an approach to handle these uncertainties is inevitable.

3 ROBUSTNESS OPTIMIZATION OF MODULES

The new approach evolves from the probabilistic RO paradigm. The system is described by a set of *m* design parameters

$$\boldsymbol{d} = [d_{1,l}, d_{1,h}, d_{2,l}, d_{2,h}, \ldots d_{m,l}, d_{m,h}] \,. \quad (1)$$

The design space $\boldsymbol{d}$ is described with lower bounds $d_{i,l}$ and upper bounds $d_{i,h}$ of each design parameter d_i. These parameters represent the design bounds for each respective standard module. In addition, *n* uncertainty parameters

$$\boldsymbol{r} = [r_1, r_2, \ldots r_n] \quad (2)$$

are defined. $\boldsymbol{r}$ contains all possible deviations during the development that influence the behavior of the simulated system. The approach works in a dual looped process, see Figure 2.

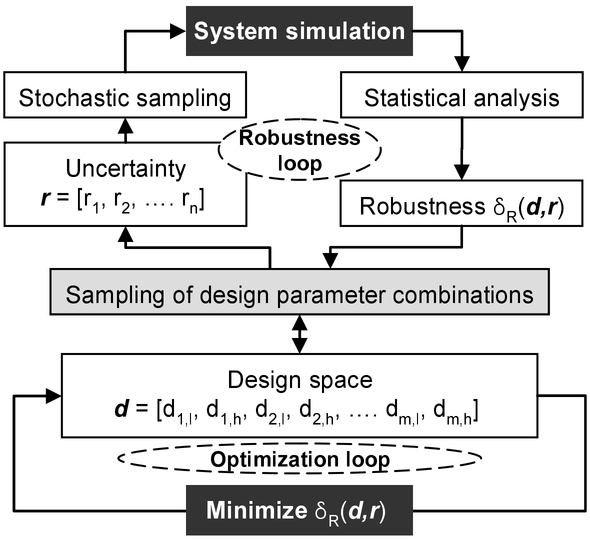

Figure 2: Overall process illustration

First, the robustness value $\delta_R(\boldsymbol{d},\boldsymbol{r})$ of a starting set of design parameters is determined within the robustness loop. Therefore, deviations $\boldsymbol{r}$ have to be added to the parameters of an initial design parameter combination. Subsequently, system simulation with different combinations of $\boldsymbol{r}$ is done based on appropriate stochastic sampling methods like Latin Hypercube Sampling. The simulation results in terms of functional requirements are then analyzed statistically. This finally results in an overall robustness value $\delta_R(\boldsymbol{d},\boldsymbol{r})$, based upon appropriate weighting of functional requirements.

Second, optimization seeks to find the best combination of design parameters for the investigated solution. In contrast to conventional probabilistic RO, it is proposed to reduce the optimization criteria to $\delta_R(\boldsymbol{d},\boldsymbol{r})$. Hence, the overall target *T* of the process can simply be identified as

$$T(\boldsymbol{d}) = min(\delta_R(\boldsymbol{d},\boldsymbol{r})) \,. \quad (3)$$

Consequently, increasing robustness of the system results in decreasing values for δ_R. This must be considered for the statistical analysis of functional requirements within the robustness loop (e.g. noise to signal ratio instead of signal to noise ratio).

Related works mainly aim at the application of probabilistic RO focusing on production and use of a product. They do not address uncertainties that modules face during their integration into the development process of different assemblies, e.g. cars. Furthermore, no evaluation methods for the robustness of those modules can be found that deal with those uncertainties. Hence, the major research effort of this paper is put on the investigation of the robustness loop.

Specification of uncertainty

The special needs of early design stages are addressed by defining uncertainty or deviation values **r**. Those uncertainties can be relatively large as one module concept contains every future car targeted by the module strategy. These uncertainties can be broken down into four types illustrated in Figure 3 and explained below.

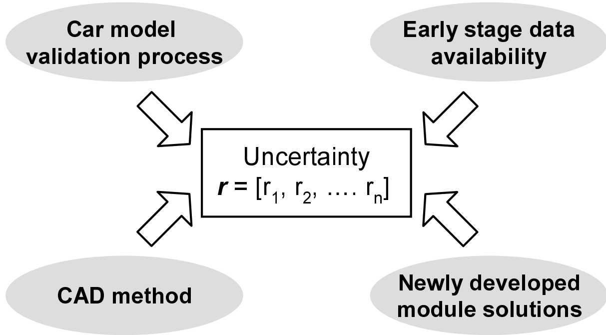

Figure 3: Uncertainties during module integration

1. Uncertainties due to the car model validation process

One of the most dominant factors for the development of a car is styling. The design of the car model is revaluated repeatedly during the car development process. This builds a major uncertainty for automotive modules because styling decisions generally don't consider potential drawbacks for the modules. Since the automotive industry established standard processes for new car projects, successor car projects and model upgrading projects, many potential uncertainties can be derived from experiences made. Those uncertainties at the interface between module and the rest of the assembled car are quantified and applied to the investigated solutions for the standard module.

2. Uncertainties due to early stage data availability

Frequently, data concerning geometry and function of parts affecting the system behavior of the module are not available at early stages. Therefore, this data has to be estimated based on similar or predecessor cars. Due to the fact that estimations quantify uncertainties, all possible variations have to be transferred into the formulation of deviation $\boldsymbol{r}$.

3. Uncertainties due to used CAD methods

Assembled automotive parts are typically mapped to common computer aided design (CAD) environments in the course of car development. However, the complexity and heterogeneity of most automotive parts disallows exact evidence about data concerning geometry and function even at the end of mass production development. Hence, every single data evolving from CAD processes is uncertain. The magnitude of deviations is dependent on the complexity and granularity of the considered data. This increases the uncertainties due to early stage data availability because every assumption based on predecessor cars cannot be exact per se.

4. Uncertainties due to newly developed modules

Simulation models of proven concepts for modules standards are typically verified holistically for different car types. Thus, those simulation models can be adapted to all targeted cars in course of the standard module development. On the other hand, the simulation models of solutions identified by inventive design approaches first have to be built. Novel solutions for modules often require more or other available space than predecessor solutions and do not fit into current cars. Therefore, most of those simulation models can only be validated and optimized decoupled from the context of the entire car and interface, respectively. The transformation of validation conclusions from isolated module testing to the context of the entire car results in uncertainties of modeling parameters of the standard module. In conclusion, this type of uncertainty mainly applies to inventive or innovative solutions.

Evaluation of robustness

Basically, all determination methods for robustness values refer to values of the output probability density function. Besides standardized formulations of the four statistic moments - mean value μ, variance σ^2, skewness *v* and kurtosis γ - robustness can also be determined by the coefficient of variation c_v or failure probability *p*. Figure 4 illustrates how to gather the robustness value of a very simple system. The system is characterized by one functional requirement, the output o1 with a related specification border. Furthermore, the uncertainty of early system evaluation is described by the scattering input parameter x1.

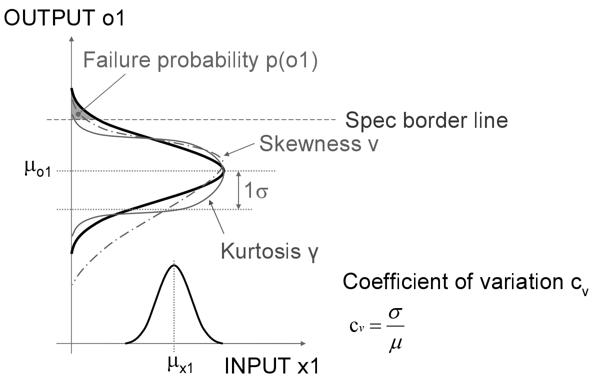

Figure 4: Scattering of one output due to input deviations

For this system, robustness is built as a weighted sum of failure probability *p* and the coefficient of variation c_v:

$$\delta_R = a \cdot p + b \cdot c_v \quad (3)$$

Both *a* and *b* represent weighting of the considered statistical values *p*, c_v. Thus, robustness evaluation can focus on different paradigms. According to Figure 5, emphasis on c_v on the left hand side leads to independency between output and input. Dominant consideration of *p* on the right hand side results in increasing reliability of functional requirements fulfillment without taking actual robustness into account.

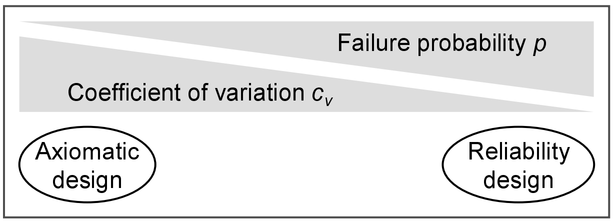

Figure 5: Possible focus of robustness evaluation

It has been shown that early design stage evaluation experiences large uncertainties. Therefore, striving for an axiomatic design seems to be the main goal. On the other hand, axiomatic designs represent theoretical ideal designs. They won't appear in reality. Furthermore, designs with a very low c_v don't regard the distance to the specification borderline of functional requirements. As input deviations are still very large due to uncertainty, the focus on the minimization of c_v easily leads to a high failure probability

Simulations based on probabilistic RO approaches tend to focus on minimizing the probability of failure in order to reach a design for six sigma. Since the large uncertainties of module integration usually preclude reaching a level of six sigma design, the new approach proposes a paradigm change.

Reaching a certain level of failure probability has to be substituted by minimizing the failure probability. Thus, failure probability is allowed in the percent range during early design stages.

All in all, overall robustness δ_R has to be evaluated on a balanced compromise of all statistical values considered. In practice, this compromise leads to an extension of functional requirements.

4 CASE STUDY

One fundamental automotive demand is to bring the latest styling trends and technologies into each product. This results in a high probability of change for early car designs. Hence, modules, which are directly dependent on the styling of the car, experience even larger uncertainties during the car integration phase. Therefore, the following case study focuses on the automatic tailgate module.

The environment of this module is characterized by a high degree of customer visibility, see Figure 6. As a result, interface modifications regarding car styling become very likely in early development stages. Those modifications have a direct effect on the performance of the module systems. Automatic tailgate concepts contain elements that apply forces from the Body-in-White (BiW) to the tailgate. This system has to work in every part of the world with high ambitions concerning comfort and safety. Therefore, high efforts have to be put into a maximum robust behavior.

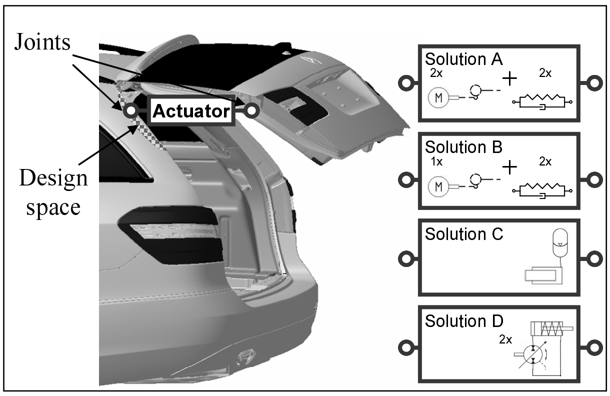

Figure 6: Simplified model of an automatic tailgate

At the beginning of a module development, designers try to span the solution space as large as possible. After a first consolidation of package and cost restrictions, there are usually about 5 to 10 feasible solutions left. These haven't yet been investigated concerning functional requirements. Figure 6 shows 4 possible solutions for automatic tailgates. The design space of all solutions can be structured into an internal and an external part. Internal design parameters like drive parameters, springs, gearboxes etc. typically allow larger variations than external design parameters like joints see Figure 6. The location of the joints plays a big role regarding kinematic behavior. Usually, the possible locations for joints at the Body-in-White are illustrated as half-opened cylinders. The geometrical characteristics of the cylinders strongly correlate with the car type. Hence, these design parameters have to be defined relatively because the standard modules have to fit into all targeted car types of a company.

Specification of uncertainty

According to chapter 2.2, some of the most relevant uncertainties for automatic tailgates are shown in table 1.

Car model validation process - location of hinge axis - design of rear lights - design of tailgate (mass and center of gravity of tailgate) - design of BiW (joints, package restrictions) - design tailgate (joints, package restrictions)	**Early stage data availability** - poor / no data availability of targeted cars → Estimations based on predecessor cars → novel future car concepts - materials of tailgate - features included in tailgate (e.g. rear camera)
CAD method - every system parameter	**Newly developed module solutions** - unexpected lifetime behavior - transformation from laboratory to reality

Table 1: Uncertainties for automatic tailgates

Evaluation of robustness

Unlike most other modules of a car, the development process of automatic tailgates is not only based on the fulfillment of strict functional requirements regarding performance (e.g. opening times) or applied loads. Rather, the behavior of the entire system during use is the fundamental development principle. Thus, the dimensions of robustness evaluation are extended in order to determine robustness considering kinematic parameters like opening angles, see Figure 7. Consequently, not only statistical values of one output probability density function are examined but also the behavior of an output plotted against the kinematic parameters [15].

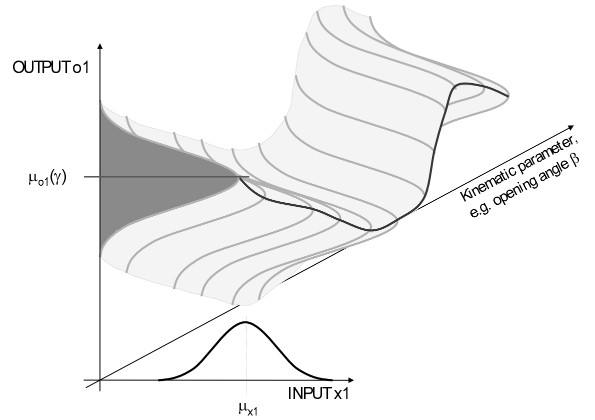

Figure 7: Dimension extension of robustness evaluation

Possible solutions for automatic tailgates have to fulfill about 80 functional requirements that can be checked as outputs in 50 use cases. In order to handle this complexity, a new method has been established to evaluate multi use-case robustness. Figure 8 shows the stepwise determination of the overall robustness value δ_R starting with the identification of statistical values of every output of each use-case. This step represents the main challenge of this method. First, the different statistical values (e.g. signal-to-noise-ratio, failure probability) have to be transformed into a comparable magnitude. Second, the specific values for behavior robustness have to be weighted. This means that all functional requirements have to be extended by weighted statistical values. Subsequently, the aggregated output robustness values result in a use-case robustness. Finally, the robustness values of differently weighted use-cases determine the overall robustness δ_R.

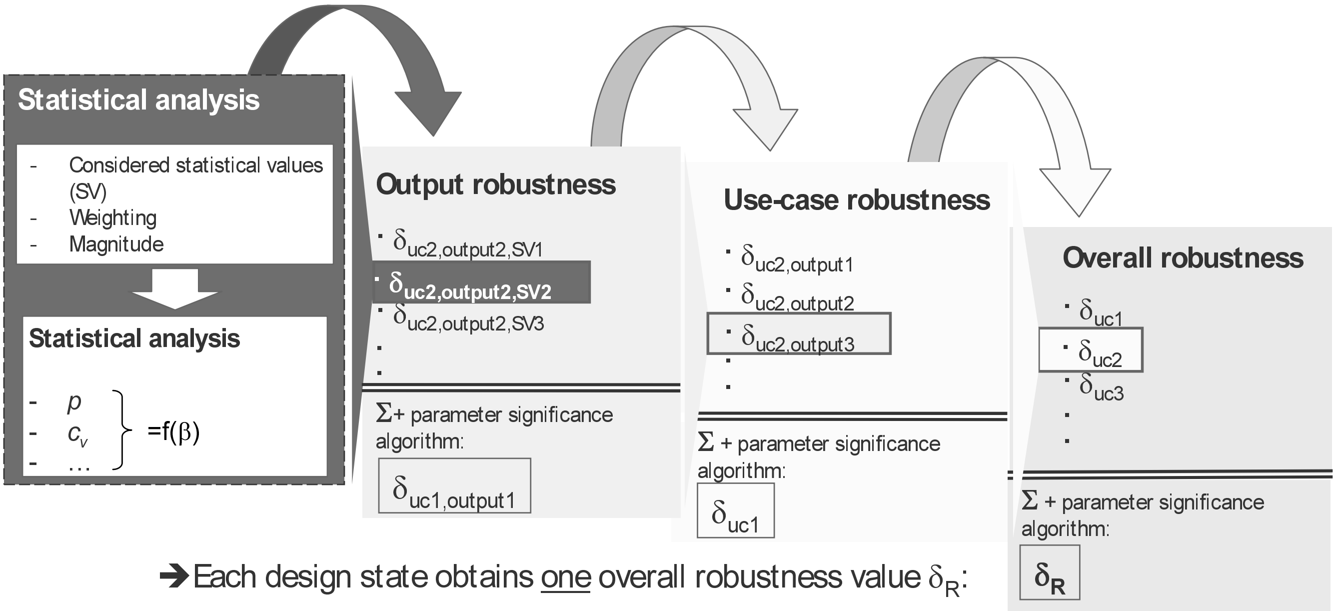

Figure 8: Multi-use-case robustness evaluation

Optimization of robustness

In contrast to probabilistic RO, the only objective of the presented approach is to minimize δ_R as all included statistical values in δ_R decrease with growing robustness. Exemplarily, two concepts have been optimized taking into account 37 statistical values of 24 considered functional requirements. The optimization has been done by an evolutionary algorithm. The robustness values of each iteration step have been determined by 30 Latin Hypercube Samples.

Figure 9 shows the results of the robustness optimization of two competing concepts for automatic tailgates in early design stage.

The solution of concept B is a one-sided electromechanical drive operating directly at the tailgate's hinge. Concept D describes a hydraulic system applying its forces by a two-sided actuator.

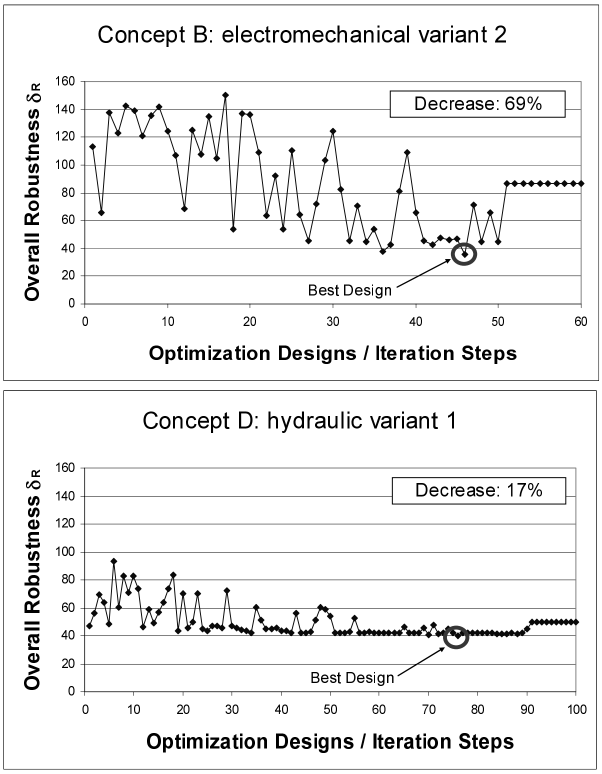

Figure 9: Results of robustness optimization of competing concepts

Concept D started with a 2.4-times better robustness value in comparison to concept B. The optimization progress of concept D shows, that its robustness value has already almost reached its best value. Concept B in opposite showed a major capability to decrease the robustness value. Finally, concept B is able to perform slightly better than concept D.

5 CONCLUSION

The presented approach focuses on the handling of early design stage uncertainties of automotive modules. It is described that the uncertainties of production and use of modules are not the focus of early design stage decisions. Rather, the uncertainties due to the integration of modules into the development process of cars are dominant. Hence, 4 types of early design stage uncertainty are identified. Those uncertainties can only be handled if their effect on the fulfillment of functional requirements is made transparent. Therefore, basic investigations concerning robustness evaluation in early design stage are demonstrated. In opposite to probabilistic RO, designers have to accept failures in percent range. Furthermore, the coefficient of variation has to be taken into account to identify actual robustness. Consequently, this leads to an extension of functional requirements. The considered statistical values of each functional requirement and their weighting have to be identified. This eventually results in an overall robustness value. Finally a conceptual optimization algorithm derived from probabilistic RO is shown. It is proposed to exclusively minimize the overall robustness value.

Following, the implementation of this paper's approach demonstrates the high unique effort which is necessary to extend the functional requirements of a showcase module automatic tailgate. Uncertainties are identified supported by the introduced structure of 4 types. Hence, robustness can be evaluated systematically. The execution of an evolutionary optimization algorithm illustrated that the minimization of the overall robustness value of two competing solutions for automatic tailgates is feasible for real problems.

In practice, the new approach requires a high unique effort for the implementation. E.g., the compromise about the extension of functional requirements has to be found on a high commitment level. Therefore, all responsible participants of module development are forced to analyze the module very early and to identify the really important functional requirements. This leads to frontloading and a higher level of transparency of the development process. Whereas robustness can be given on a technical basis, humans still have to use and execute the approach. This leads to questions concerning process robustness. Therefore, further research focuses on the human role and influence of the approach.

Additionally, the approach enables developers to take inventive and innovative solutions for automotive modules into account. However, this can result in a large solution space. In order to handle this complexity, methods and tools for the automation of the process have to be found. Combined with the premise of full embedding capability into car development, the process automation seeks to simplify and standardize further module development.

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