Early Robust Design Approach for Accelerated Automotive Innovation Processes

Fabian Wuttke, Martin Bohn, Nick-Ange Suyam-Welakwe

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Fabian Wuttke[1, 2], Martin Bohn[2], Nick-Ange Suyam-Welakwe[2]

[1] Institute for Information Management in Engineering, Karlsruhe Institute of Technology
Germany
[2] Daimler AG
Germany
{Fabian.Wuttke, Martin.Bohn, Nick-Ange.Suyam_Welakwe}@daimler.com

Abstract. The shift to modularized cars leads to the need for early and precise concept decisions for the development of modules. Many module definitions focus on the interaction between modules to make them upgradeable. The focus here is on modules that have to work with unknown restrictions in terms of uncertainty. In this paper, emphasis is put on unknown car styling in early design stages. Because of frequent interface modifications during the validation process of car styling, the great influence of this unknown restriction on modules is discussed for kinematic systems. The systematic approach of Robust Kinematics Optimization is successively described and exemplified. Due to the early and computer-aided consideration of uncertainties, the developer is able to judge even very unconventional and innovative module concepts. Furthermore, a higher level of transparency is achieved in concept decisions because the consequences of modifications during later development stages have been precociously integrated and validated.

Keywords: Early Design Stage, Integration of Innovation, Robust Design Optimization, Automotive Development Process

1 Introduction

In recent years, the automotive development methods have moved from hardware-dominated application and testing to virtual validation of vehicles, systems and components. As a result of lower costs for software compared to hardware, this strongly downsizes or even eliminates hardware testing phases in standard development processes. Due to additionally decreasing product development times in combination with extending numbers of platform derivates, one of the major current challenges in the automotive industry is the need for precise, rapid and robust concept decisions in early design stages. Therefore, new approaches and methodologies in terms of computer-aided innovation are needed in order to increase the maturity of virtual validation.

1.1 Early design stages in styling-driven automotive industry

Current development standards are characterized by simultaneous development phases. The actual development as shown in fig.1 is usually structured into the phases “strategic development”, “preliminary development” and “mass-production development”. In this paper, the focus strictly is on the early stages of strategic and preliminary development as computer-aided innovation (CAI) unfolds most impact there [12,16].

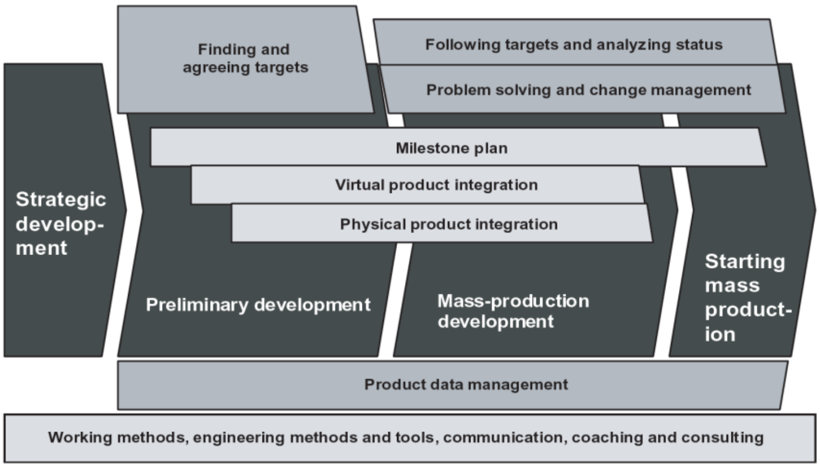

Fig. 1. Overall illustration of the product generation process [17].

Especially in the automotive industry, there is a huge difference in terms of standard timetables and processes between a new-, change- or adaptation car design. Therefore, most companies established adaptive standard processes distinguishing between new car projects, successor car projects and model upgrading projects [2].

Although the standard processes for developing the entire car might differ, the thought of unitized cars from component’s perception is more and more commanding in today’s car development. Unitized car means that a vehicle is assembled by a certain amount of modules (gear boxes, bumpers, breaks, seats, actuators for automatic tailgates, etc.) [19,20]. [9] underline the necessity of modular product architecture especially when the development of complete subsystems or components is performed by different teams in different locations. This is the case in the automotive area, where a lot of systems and components are coming from suppliers. The goal is that the modules are standardized comprehensively within an OEM and can be adapted specifically for each car project. Additionally, from the engineering point of view, module based product development contributes to a better management of complexity, makes parallel product development possible and enables better control of future uncertainties [4]. The latter is possible because modules can be seen as “functional black boxes”, which can be developed and tested separately. However, a clear definition of the interfaces between the modules and their environment is a prerequisite to benefit from the module approach [9]. With this in mind, [15] “consider complex products as a network of components that share technical interfaces in order to function as a whole”.

This module paradigm leads to reduced costs because of scaling effects. But usually, the development of the 1-2 standards for each module bases on experience and expertise of engineers and does not necessarily integrate the influence of new car projects. This might eventually lead to suboptimal results if the styling of new cars leads to unconsidered effects for the modules themselves, see fig. 2.

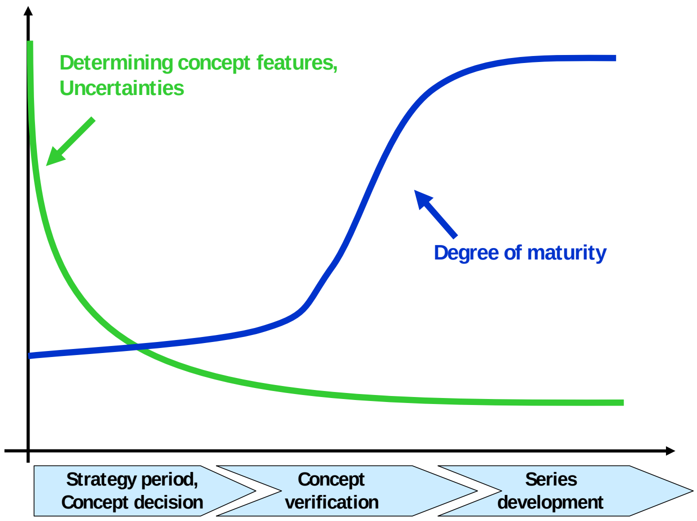

Fig. 2. Basic dilemma of module concept decisions

Furthermore, new inventive methods like TRIZ are eager to help both suppliers and OEM’s to reach unconventional solutions for modules beyond the previous experience of the engineers. But the advancing implementation of those methods discussed in research works such as [6] only will establish and unfold their full power, if all uncertainties are precociously validated.

1.2 Kinematic system modules in the automotive industry

Especially modules that are directly dependent on the styling of the car are often faced with improvable behavior of early developed module concepts when it comes to the mass-production development. One example being investigated within this paper are the modules that one can aggregate by so called „kinematic systems“. In this paper, kinematic systems are defined as multi body systems containing nonlinear movements, which are usually characterized by a closed mechatronic system behavior. Namely, it’s window lifters, retractable tops or automatic rear lids and tailgates. Those modules are typified by a high degree of customer visibility. Hence, interface modifications regarding car styling become very likely in early development stages. However, those modifications can have a direct effect on the performance of the module systems. Investigated modules often showed high sensitivities of interface parameters concerning the entire system behavior. Moreover, kinematic systems are not developed and produced by the original equipment manufacturers (OEM) themselves but are mainly left responsible at the suppliers both during production and development stages. The behavior of the entire kinematic system still remains within the responsibility of the OEM's which additionally brings challenges in terms of shared development [18].

1.3 Early evaluation loops of kinematic systems

In fact, the development of innovative modules requires very early evidence about the fulfillment of functional requirements in partly very different car concepts. For this purpose, the boundary conditions of similar- or predecessor car concepts are being consulted. On this basis, simulations should verify the operability for the target car concepts.

For the computation of such mechatronic systems, CAE programs are already established. In accordance with verified input parameters and validated simulation models, evidence about the behavior of one model draft can already be given. This approach has proven successful in the analysis of systems that are yet mass-produced [14]. Unfortunately, these investigations discount the following uncertainties, which are immanent regarding the standard methods:

1. Decisions of management regarding the car styling in the context of the model validation process.
2. Poor data availability of car components during early development stages (strategic und preliminary stage).
3. Uncertainties due to CAD methods: Difficult data gathering of hybrid, complex assembly structures.
4. Uncertainties due to verification methods: Simulation models of new, innovative module concepts can only be validated separately from the car or interface context. The gap between module behavior in the laboratory and in the car is not taken into account.

At this point, the necessity for a new computer-aided approach becomes obvious. This approach has to help innovative module concepts to a considerably higher degree of maturity in early design stages as well as it has to bring more transparency throughout the whole automotive model styling validation process.

The problems shown before affect some different aspects of computer-aided innovation. Recent research activities like [7] intensively investigated the question of how to systematically come to innovative or inventive products. 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 development. However, the demanding functional requirements of the automotive industry combined with the high sensitivity for uncertainties leads to problems of inventiveness-driven tools established lately. As a consequence, engineers tend to fall back to proven and tested conventional modules. To support the engineer within this basic dilemma, tools of parameterization and automation emerged. One example is design automation (DA) discussed in [8]. Based on explicit information of existing parts, concepts can be rapidly adapted to different boundary conditions. Other approaches of parameterization like [10] enable the automatic investigation of different designs. However, all investigated computer-aided innovation methods do not regard uncertainties of the development process. The handling of strategic uncertainties is topic of [11]. But the very generic view on uncertainties disallows the implementation in terms of mathematical-based CAI.

2 RKO – Robust Kinematics Optimization

During research on this computer-aided innovation approach, two fundamental questions were figured out:

1. How to ensure that the competing module concepts for kinematic systems are evaluated with their optimal parameters?
2. How to manage uncertainties in the early design stages?

Basically, these questions address the problem of how uncertainties in early stages of a module development can be evaluated systematically as well as how the impact of uncertainties can be reliably minimized. This elementary topic has been investigated in the area of Robust Design Optimization (RDO) for a while. Following, the basics of RDO are explained in order to illustrate the necessary adaptations to be able to evaluate robustness of kinematic systems and to optimize the behavior and performance of arbitrary module concepts in early design stages.

2.1 Basic idea of Robust Design Optimization

Originally, the idea of the Robust Design Optimization (RDO) developed from classical optimization strategies, which optimized components in topology or shape according to defined objective functions. However, since uncertainties in the mass production (e.g. variations in terms of material properties, component geometry) were ignored, a higher percentage of scrap was the result of unconsidered and unexpected deviations in series process. To minimize the high costs of meeting the target quality, the idea of a zero-defect production established itself. This paradigm is not focused on the optimization of production processes, but on the optimization of the component design in order to make the design insensitive to possible variations in mass production. For this purpose, all relevant parameters are afflicted with production-specific tolerances. Subsequently, the impact on the fulfillment of the objective functions is determined. At this point, literature distinguishes between "Robustness evaluation" ($<\pm 2\sigma$) and "Reliability Analysis" ($<\pm 6\sigma$) [13]. In order to carry out an assessment in the area of Reliability Analysis ($<\pm 6\sigma$), very accurate knowledge on the considered production process is needed. Since this is not possible in early design phases, all further analyses of variance in this paper are limited to a safety level less than $\pm 2\sigma$.

Basically, a RDO task contains a set of m design parameters

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

that are afflicted with defined variation boundaries di,l, di,h . In addition, r variances

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

are defined. ***r*** contains scattering of design parameters as well as of parameter which cannot be influenced by development. Ordinary RDO approaches work in a dual-looped process. First, the robustness value $\delta_R(\boldsymbol{d,r})$ of one random set of design parameters inside its boundary conditions is determined within the inner loop. Second, the design parameters ***d*** are given other random values and the robustness is re-evaluated. The second, outer loop is usually done by stochastic optimization algorithms such as genetic algorithms, Monte Carlo simulation or particle swarm optimization. The target *T* of the RDO process can simply be identified as

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

In other words, the robustness value δ_R as indicator to the overall sensitivity of output parameters versus input parameters has to be as small as possible. Then, scattering ***r*** exerts minimal influence on the output and functional requirements, respectively [3].

2.2 Definition of robustness

The major challenge within RDO is the inner loop being responsible for the valid evaluation of robustness. Basically, all determination methods for robustness values refer to the values of the output probability density function like shown in fig. 3.

Conventional methods like Taguchi's loss function interpret the variation from the expected mean value μ_{o1} as actual monetary loss and hence try to minimize deviation of predicted output values from target values [5]. Other approaches minimize failure probability $p(o_1)$ or assess statistical parameters of the output distribution function like mean value μ in ratio to standard deviation σ, skewness *ν* or even kurtosis γ.

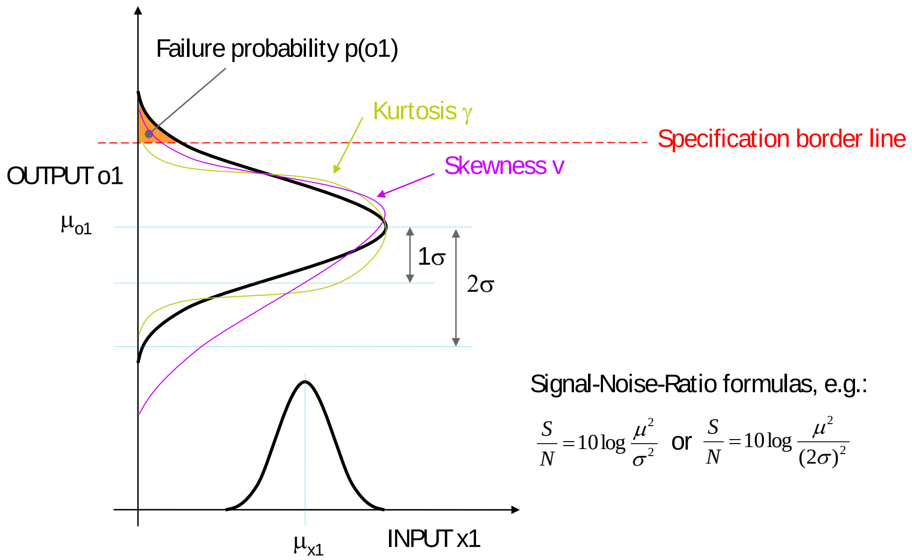

Fig. 3. Possible scattering of one output due to input deviations

These default approaches measure robustness on the basis of one or more outputs and cumulate the single robustness values resulting in an overall robustness. This method has proven successful in Finite-Element-Analysis-dominated RDO research. However, RDO focuses on the early consideration of production tolerances but not on the special challenges of early design uncertainties. Furthermore, the rating of one output in terms of the result of FEM simulation is not sufficient regarding the robustness evaluation of kinematic systems.

2.3 Robust kinematics optimization

The reason for this is that the development process of kinematic systems is not only based on the fulfillment of strict functional requirements regarding performance (e.g. opening times) and applied loads, respectively. Rather, the behavior of the entire system afield has to become the fundamental development principle. Thus, Robust Kinematics optimization (RKO) as further development to RDO extends the evaluation dimensions in order to determine robustness considering kinematic parameters like opening angles. Fig. 4 shows the example of an output value o1. Illustrated in grey color, a couple of probability density functions of o1 are shown for different opening angles β. By interpolation between the probability density functions it is possible to analyze the behavior of statistical parameters. E.g., the characteristics of the mean value $\mu_o(\beta)$ can easily be visualized, see red curve in fig. 4.

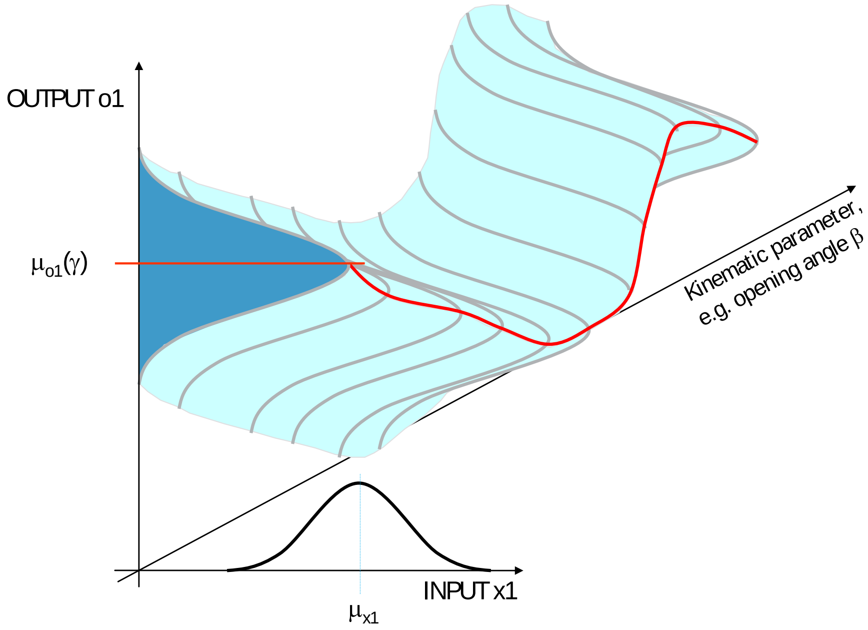

Fig. 4. Dimension extension of the robustness evaluation process in the framework of RKO

For instance, let the computed standard deviation 2σ of an arbitrary output parameter o_i be considered as good regarding robustness when the kinematic system is closed (β=0). Subsequently, RKO investigates the behavior of 2σ plotted against the opening angle. If the robust standard deviation 2σ drifts from its original value, the investigated set of design parameters has to be considered less robust as it would have been conventionally assumed. Simulation results showed that the computed robustness values (e.g. 2σ, μ, $p(o_i)$) differ considerably when assessed over an entire kinematic parameter. Only with this further step in addition to RDO the systematic investigation of robustness of behavior for kinematic systems becomes possible.

The computer-aided innovation based on RKO envisions the following systematic approach.

1. Specification of robustness: Initially, the bounds for allowed robustness value drifts have to be determined for each investigated use-case and functional requirement output, respectively.
2. Specification of design space: The simulation model of the considered module concept is given initial design parameters $\mathbf{d_1}$ which contain reasonable parameters for the interface, i.e. styling of a predecessor car compatible best to the intended car projects for the investigated module concept. Furthermore, design space in terms of boundary conditions $\mathbf{d_{i,l}}$, $\mathbf{d_{i,h}}$ have to be determined on basis of the experience made in previous car projects.
3. Specification of uncertainty: The next step integrates the special needs of early design stages by defining uncertainty or scattering values **r**. Those uncertainties can be relatively large as one module concept should fit into possibly every future

car containing the investigated kinematic system framework. Additionally, the values of **r** are usually interdependent.

4. Optimization of robustness: Once uncertainties have been systematically built, the overall robustness of initial design parameters $\mathbf{d_1}$ can be determined. Following, the actual optimization takes place. Therefore, the upper and lower bounds of all design parameters have to be adapted. Those bounds again are usually interdependent due to different car types. At this stage, everything is prepared for a stochastic optimization. The goal of the optimization is to find the optimal design parameters of the module concept $\mathbf{d_m} \in \mathbf{d}$ that represent maximum robustness of the behavior of the kinematic system when afflicted with uncertainties due to early design stage problems. Thus, the systematic robustness evaluation of step 3 has to be done after every optimization step. Regarding minimal influence of the robustness of the optimization algorithm itself, genetic algorithms as evolutionary computational tools fit best as they showed good results in related works [1].

2.4 Example

To illustrate the approach of RKO shown in section 2.3, the method is applied on an example for kinematic system modules. For this purpose, automatic tailgates as shown in fig. 5 are qualified best. This is because the influence of different target car types and styling decisions on automatic tailgates is unquestioned in course of the automotive development process.

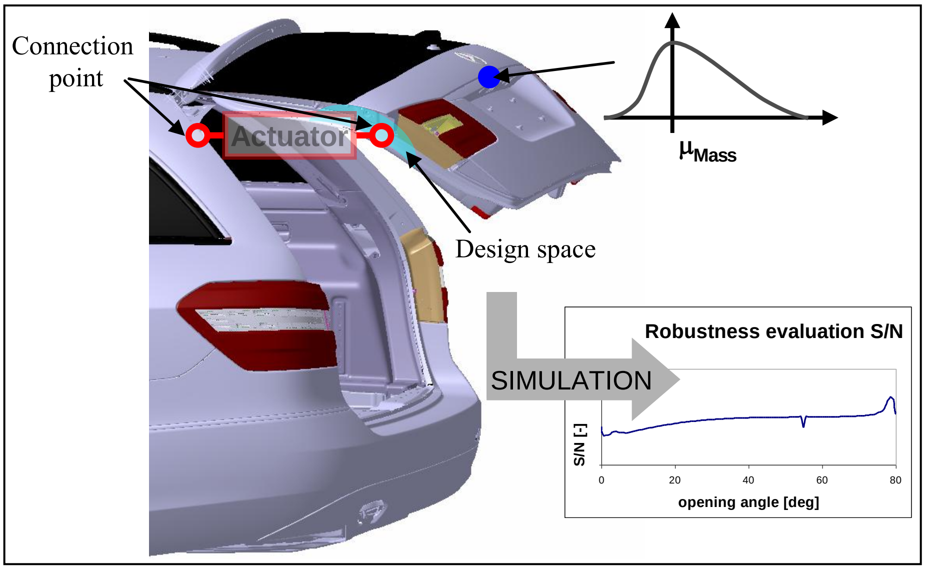

Fig. 5. Simplified model of an automatic tailgate

The following explanations are held simplified in order to make RKO tangible within this paper. However, the main idea remains the same also for the complex overall optimization process for kinematic systems.

1. Specification of robustness: Based on very intense adjustment talks with experienced engineers, the considered robustness values as well as their respective drift penalties have to be determined. This must be done once for a kinematic system in course of the definition of functional requirements for the entire system. Later, module developers will access the limit definitions without higher efforts. The given example for robustness value drift will be the simple Signal-Noise-Ratio

$$S / N = \mu / \sigma \qquad \textbf{(4)}$$

of the necessary torque of a spindle actuator that moves the tailgate plotted against the opening angle.
2. Specification of design space: As soon as module development has decided on the targeted car types, the design boundaries have to be determined. E.g., automatic tailgate concepts for sports utility vehicles (SUV) as well as for station wagons contain elements that apply forces from the Body-in-White (BiW) to the tailgate. The location of the connection points of those elements plays a big role regarding kinematic behavior. Usually, the possible locations for connection points at the BiW can be illustrated as half-opened cylinders. The radius and possible bending of the cylinders strongly correlate with the investigated car type. Hence, the design parameters depend on the car type and have to be defined relatively. To start RKO, initial design parameters are adopted from the concept most similar to the targeted car types, e.g. the latest SUV. In case of unavailability of similar starting points, arbitrary initial parameters can be taken as long as they stay within the boundary design conditions.
3. Specification of uncertainty: One of the most obvious uncertainties of automatic tailgates comes from the design process of the tailgate itself. Namely, the weight of a hardware-tailgate usually differs significantly from the original assumption of early design stages. Furthermore, interdependent scattering parameters can be identified for automatic tailgates. Module concepts of automatic tailgates have to be capable of actuating the tailgates of an SUV as well as of a station wagon. Since the tailgate shapes essentially differ between an SUV and a station wagon in terms of thickness, mass, slope and especially interface design, the styling uncertainties included in **r** depend on the car type. This means that the design constraints of BiW that build the main interface uncertainties to the module vary subject to the car model. In order to attract as many customers as possible, the design of cars is strongly based on styling decisions. Those styling decisions are typically made on top management level and seek to include future trends and needs of customers. In opposite to design uncertainties like weight predictions, styling uncertainties cannot be derived from experiences. On the one hand, sharp ranges and borders of scattering functions can hardly be determined. On the other hand, uncertainties of early design stages are never exactly specified regarding their borders or distribution. I.e. borders of weight prediction are estimated and hence represent a trend, though more precise than styling predictions. The underlying approach of RKO strives to optimize a system's robustness on the basis of uncertain parameters. As those uncertainties remain constant over the optimization process, robustness values are compared not absolute but relative to each other in order to find the best system parameters. Hence, trends in styling can be included in RKO

even if their parameters are rather predicted qualitatively. Based on estimations of styling departments, the main challenge is the complex formulation and parameterization of those highly interdependent uncertainties.

4. Optimization of robustness: The double-looped optimization process firstly evaluates the robustness of the entire system. For the simplified example investigated in this section, the initial design parameter combination $\mathbf{d_1}$ is established with the connection points for force-applying elements of the last SUV or station wagon released to the market. Then, uncertainties like deviation in mass or scattering of the above-mentioned connection points are applied. Subsequently, a robustness evaluation algorithm samples a certain amount of stochastic combinations of uncertainty deviations. The actual robustness values are determined by investigating the scattering of the necessary torque in terms of identifying the 2σ-level. At this point, genetic algorithms start to mutate and crossover design parameters within their bounds and the robustness can be re-evaluated with a new set of design parameters. The final result of this evolutionary optimization will be a combination of design parameters with the minimum-possible 2σ-level of the necessary torque plotted against the opening angle of the tailgate. I.e. that evolutionary algorithms find the one design parameter set $\mathbf{d_m}$ for an arbitrary module concept which is optimal robust against all uncertainties brought by the early design stage dilemma.

2.5 Contribution to Computer Aided Innovation

The implementation of the RKO standard introduced in section 2.3 enables the developers of standard modules to establish a considerably higher level of maturity and transparency during early design stages. The major input for the developer is uncertainty due to early design stage. These uncertainties have to be disclosed and discussed in the framework of module development. Furthermore, the degrees of freedom for module design parameters $\mathbf{d_m}$ have to be presented openly. Once all parties agree to the assumptions, the developer is free to test established module concepts as well as very creative and inventive concept drafts. This is because the holistic approach of RKO allows the rapid investigation of innovative ideas within the framework of clarified and visible boundary conditions. See fig. 6.

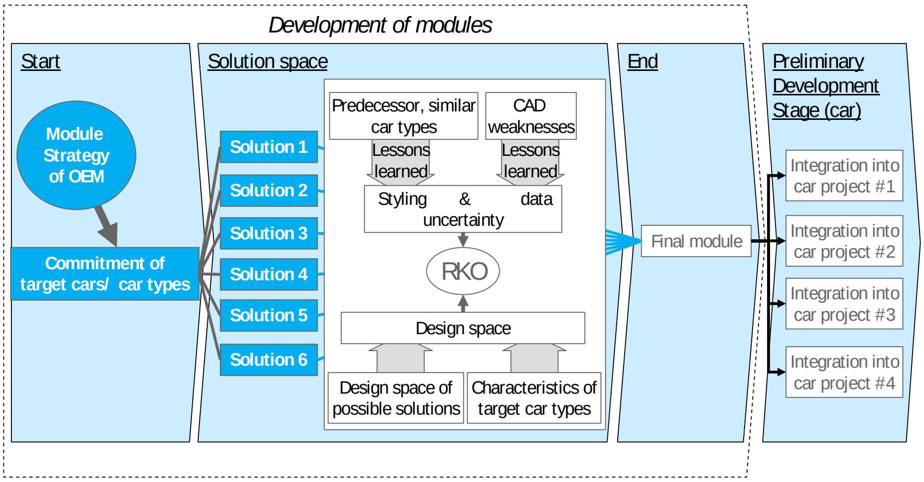

Fig. 6. Integration of RKO into standard automotive development process

Of course, the uncertainties considered in the earliest design stages narrow in the course of later development stages. But having assured that the designed module fits best into the targeted cars and is optimally robust against immanent uncertainties during car development, the degree of maturity necessarily increases further in later development phases. This means that the behavior of outputs becomes even more robust because input deviations decrease. The behavior of outputs is equal to the fulfillment of functional requirements. Hence, late design decisions have a minimal influence on the fulfillment of functional requirements and the necessity to change functional requirements of automatic tailgates is minimized. Ultimately, the high degree of transparency offered by the method of RKO leads to more sustainability in management decisions because all participating parties had to commit to the boundary conditions for module development in early stages.

3 Conclusion

This paper started with a classification of module-based development in the course of early design stages in the automotive industry. Subsequently, kinematic systems in the automotive industry were introduced representing a special class of modules that are usually faced with high uncertainties of interface design due to frequent exterior styling modifications. The basic dilemma of high uncertainties versus the need for precise concept decisions of large-scaled modules lead to the need for a systematic, computer-aided approach that enables innovative modules to unfold their full abilities of modularization. Established CAE technologies in the area of Kinematic systems neglect design parameter variations as well as uncertainties in the later course of product development. The needs for variation of parameters and consideration of uncertainty within the development of Kinematic system modules have been investigated in the area of Robust Design Optimization for a while. Therefore, the research effort within this paper focused on the necessary modifications in order to introduce Robust Kinematics Optimization. The envisioned process shows the high unique effort necessary for the implementation of Robust Kinematics Optimization as well as the huge benefits for every further development of modules. The idea of this computer-aided innovation was afterwards illustrated using the example of automatic tailgates as highly styling-dependent modules. Finally, the impact of Robust Kinematics Optimization was shown. Because of higher transparency as basis for concept decisions in early design stages, the developer may unfold and consider all possible and also unconventional concept ideas as all usual uncertainties are integrated in this computer-aided innovation approach.

Exterior design decisions are usually made regarding the appearance of a whole car. Recent experiences showed that the assumptions made for styling uncertainties are only relevant as long as the design strategy remains constant. Unfortunately, the customer's decision is dominated by the judgment over the car styling, especially in the luxury segment. Subsequently, modifications or evolutions of the car styling will remain an immanent aspect of the car development as the customer's opinion is volatile. Eventually, the uncertainties agreed by the management also remain afflicted with uncertainties. But with the systematic approach of Robust Kinematics Optimization, the developer is able to quickly handle changed circumstances and re-evaluate his decision.

References

1 Albers, A; Leon Rovira, N; Aguayo, H; Maier, T: Optimization with Genetic Algorithms and Splines as a way for Computer Aided Innovation. Follow up of an example with crankshafts, 2008, in IFIP International Federation for Information Processing, Volume 277; Computer-Aided Innovation (CAI); Gaetano Cascini; Boston: Springer, pp.7-18.

2 Balasubramanian, B: Entwicklungsprozesse für Kraftfahrzeuge unter den Einflüssen von Globalisierung und Lokalisierung, 2008, Forschung für das Auto von Morgen (Ed. Schindler, V; Sievers, I), Part 3, Berlin, Heidelberg: Springer, pp. 349-362.

3 Ben-Tal, A; Nemirovski, A: Robust optimization – methodology and applications, 2002, Mathematical Programming (Series B), vol. 92, pp. 453 – 480.

4 Baldwin, C; Clark, K: Modularity in the Design of Complex Engineering Systems, 2006, in Complex Engineered Systems: Science Meets Technology, edited by Ali Minai, Dan Braha and Yaneer Bar Yam. New England Complex Systems Institute Series on Complexity. New York: Springer.

5 Byrne, D; Taguchi, S: The taguchi approach to parameter design, 1986, Proceedings of the 40th Anniversary Quality Congress Transactions, American Society for Quality, Milwaukee, Wisconsin, pp. 168-175.

6 Cavallucci, D; Rousselot, F; Zanni, C: Representing and selecting problems through contradictions clouds, 2008, in IFIP International Federation for Information Processing, Volume 277; *Computer-Aided Innovation (CAI)*; Gaetano Cascini; (Boston: Springer), pp. 43–56.

7 Cavallucci, D; Eltzer T: Improving the Relevance of R&D's Problem Solving Activities in Inventive Design Context, 2007, 16th International Conference on Engineering Design, ICED'07, Ecole Centrale Paris, Paris.

8 Colombo, G; Pugliese, D; Rizzi, C: Developing DA Applications in SMEs Industrial Context, 2008, in IFIP International Federation for Information Processing, vol. 277; *Computer-Aided Innovation (CAI)*; Gaetano Cascini; Boston: Springer, pp. 69–82.
9 Eppinger, S; Chitkara, A: The Practice of Global Product Development, 2007, IEEE Transactions on Engineering Management, vol. 35, no. 1, pp. 3-12.
10 Leon, N; Cueva, J; Villarreal, C; Hutron, S; Campero, G: Automatic shape variations for optimization and innovation. Shape Optimization of Cylinderhead Gasket using CFD, 2007, in IFIP International Federation for Information Processing, Volume 250, Trends in Computer Aided Innovation, ed. Leon-Rovira, N., (Boston: Springer), pp. 179-188.
11 Lorenz, M: Handling of Strategic Uncertainties in Integrated Product Development, 2008, Dissertation, TU Munich.
12 Pahl, G; Beitz, W; Feldhusen, J; Grote, K-H; Wallace, K; Blessing, L: Engineering Design: A Systematic Approach, 2007, 3rd Edition, Berlin, Heidelberg, New York: Springer.
13 Roos, D; Adam, U; Bucher, C: Robust Design Optimization, 2006, Proceedings Weimar Optimization and Stochastik Days 3.0, Weimar.
14 Sinha, R; Paredis, C; Khosla, P: Integration of mechanical cad and behavioral modeling, 2000, Proceedings of the IEEE/ACM Workshop on Behavioral Modeling and Simulation.
15 Sosa, M; Eppinger, S; Rowles, C: A Network Approach to Define Modularity of Components in Complex Products, 2007, ASME Journal of Mechanical Design, vol. 129, no. 11, pp. 1118-1129.
16 VDI 2221: Systematic approach to the design of technical systems and products, 1993, Berlin: Beuth.
17 VDI 2243: Recycling-oriented product development, 2002, Berlin: Beuth.
18 Walker, A J; Cox, J J: Virtual Product Development Models: Characterization of Global Geographic Issues, 2008, in IFIP International Federation for Information Processing, Volume 277; *Computer-Aided Innovation (CAI)*; Gaetano Cascini; (Boston: Springer), pp. 119–131.
19 Winterkorn, M: Speech in the course of the annual stockholders meeting, Volkswagen AG, 2010, Germany. Available at http://www.volkswagenag.com/vwag/vwcorp/info_center/de/talks_and_presentations/2010/04/Part_III.-bin.acq/qual-BinaryStorageItem.Single.File/Teil%20III%20Charts%20Prof.%20Dr.%20Winterkorn.pdf
20 Zetsche, D: Speech in the course of the annual stockholders meeting, Daimler AG, 2010, Germany. Available at http://www.daimler.com/Projects/c2c/channel/documents/1827847_daimler_ir_hv2010_rede.pdf