EARLY ROBUSTNESS OPTIMIZATION OF AUTOMOTIVE MODULES – REGARDING THE KEY IMPACT OF THE HUMAN FACTOR

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ABSTRACT
In the context of module based car development, standard modules face large uncertainties during their integration into the development process of the car. Therefore, a high level of robustness of standard modules is needed. A method is presented to increase and optimize robustness on the technical side. In addition to the technical perspective, the human role is also considered. This paper aims at identifying the demands of the method on designers as well as the designer's requirement on the method. The discrepancy between these two demands determines the robustness of the process. Hence, robustness is evaluated holistically, including both the technical and the process side considering the human factor.

Keywords: Product robustness, process robustness, human factor, early design stage, module development

1 INTRODUCTION
The trend in today's car industry is towards more variants and lower volume. To achieve the target costs, it is necessary to use standard modules across several car lines. It is also a common trend to reduce development time and hardware prototypes. Both issues alone are manageable. The challenge can occur with the combination of both, when it is necessary to develop a module without knowing the restrictions of future car models. This requires very robust modules to handle these uncertainties. To achieve this goal, a methodology for robustness optimization is necessary as well as an optimal use of the robustness optimization tool. Therefore, the human factor has to be taken into account.

1.1 Module Based Development
According to Baldwin and Clark [1], module based product development contributes to a better management of complexity, makes parallel product development possible and enables better control of future uncertainties. The latter is possible because modules can be seen as "functional black boxes", which can be developed and tested separately. In recent years, the module approach spread out over many industries including software development, machine tooling or the car industry. In the car industry, the goal for a working module approach is to have each car assembled by a certain amount of modules. Companies ideally 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 entire company, see Figure 1.

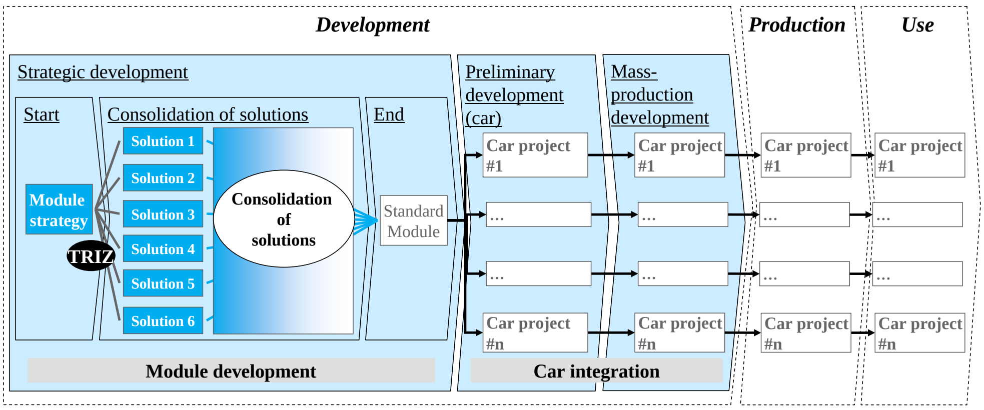

Figure 1. Module Based Development process [2]

The automotive development process is structured into the phases ‘strategic development’, ‘preliminary development’ and ‘mass-production development’. Standards for modules are developed within the strategic development phase. Later automotive development stages focus on the integration of those modules into the assembled product.

1.2 Challenges of Early Design Stage

Uncertainties are present during every stage of product development as well as during production and usage of the final product, see Figure 2. Typically, large uncertainties at the beginning of the car development process decrease over time and reach 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.

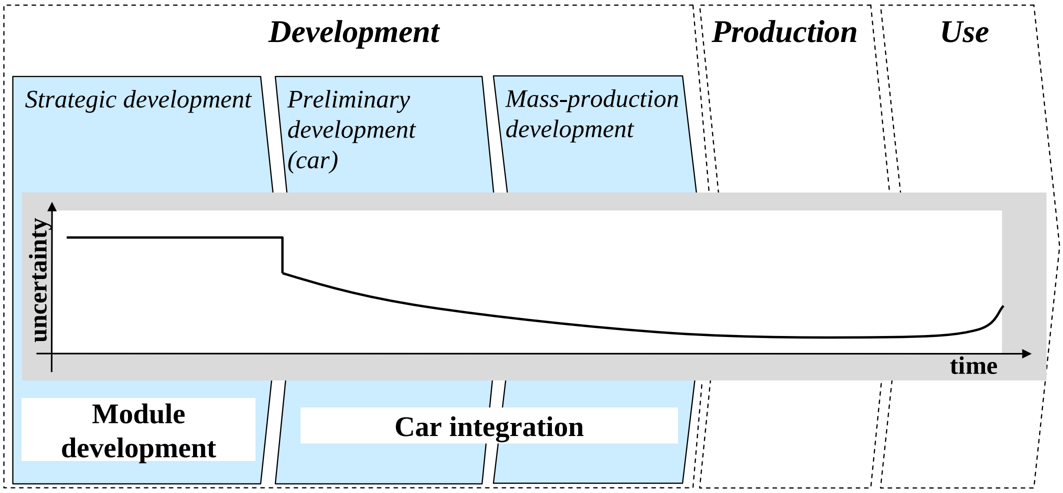

Figure 2. Uncertainty during Standard Module Development and Car Integration

As illustrated in Figure 2, the decision about the standard module has to be made in the beginning and influenced by the highest level of uncertainty possible. Therefore, one major issue of module development is the question which solution is best capable of handling deviations in terms of restrictions due to the car integration process. Currently, no method is established in module based development processes 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 which could be found by inventive design methodologies.

Additionally, the neglect of uncertainties within the development of a standard module typically leads to high costs during the later car integration phases due to additional work to update the module. That is because previously unknown uncertainties can affect proven solutions when unknown, novel car types appear in future projects.

1.3 Consequences for Innovation Capability

At the beginning of module development, developers strive to obtain the maximum number of possible solutions. Therefore, both conventional and inventive development methods like TRIZ [3] 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 even tools [4]. 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 combined with the high sensitivity for uncertainties leads to problems of acceptance of such tools.

Furthermore, the consolidation of different solutions for standard modules historically results in proved solutions. This is because practitioners have no method to handle the uncertainties influencing innovative solutions during car development. As a consequence, designers tend to fall back to proven and tested conventional modules.

2 TECHNICAL ROBUSTNESS OF AUTOMOTIVE MODULES

2.1 Basic approach

When investigating the robustness of a product, the so call P-diagram is often taken into account [5]. P-diagrams visualize the relation between the product outputs and the influencing factors. Figure 3 shows the P-diagram of solutions for standard modules.

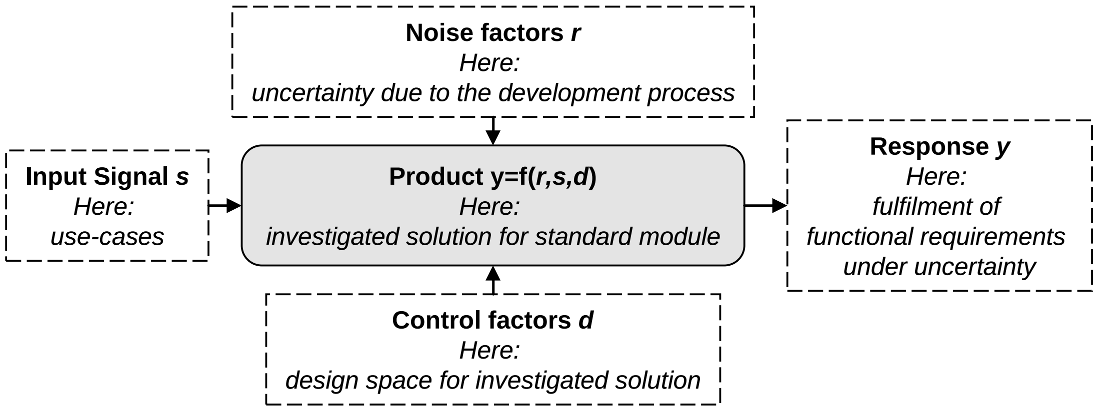

Figure 3. P-Diagram of Solutions for Standard Modules

According to Figure 3, the product's performance depends on 3 influencing factors. In the automotive industry, modules have to work under very different external conditions. According to Taguchi [6], automotive modules have to be classified as dynamic systems, extending the P-Diagram by input signals. The different conditions are typically checked by use-cases which are described here as input signals $\boldsymbol{s}$. Moreover, the investigated solutions can be designed differently, especially during early design stages. From the perspective of P-diagrams, this design space is illustrated by the control factors $\boldsymbol{d}$. Both $\boldsymbol{s}$ and $\boldsymbol{d}$ can easily be identified within the framework of functional requirements and the investigated solutions. During the consolidation of different solutions, the influence of uncertainty for later integration of standard modules into the car development process is dominant. Unfortunately, there is no method available to identify those uncertainties $\boldsymbol{r}$. Therefore, emphasis has to be put on the identification of $\boldsymbol{r}$ in order to evaluate and finally increase the robustness of standard modules.

2.2 Early Robustness Optimization (ERO)

The new approach evolves from the probabilistic Robust Optimization (RO) paradigm [7]. The system is described by a set of *m* design parameters

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

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

$$\boldsymbol{r} = [r_1, r_2, \ldots. r_n] \tag{2}$$

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 4.

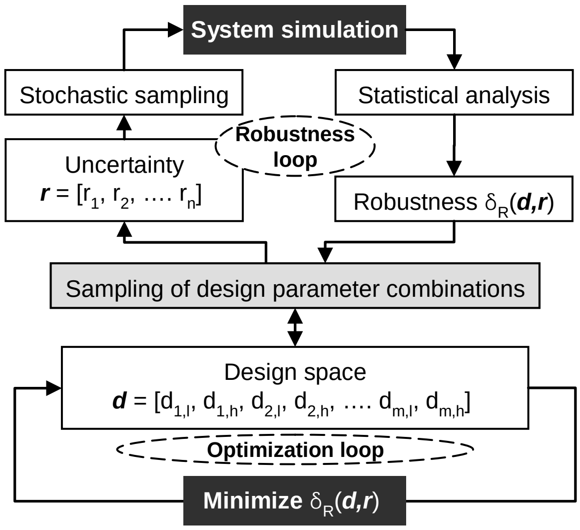

Figure 4. Process illustration of Early Robustness Optimization

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. The result is 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 work mainly aims at the application of probabilistic RO focusing on production and usage 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 are capable to handle those uncertainties. Hence, the major contribution of Early Robustness Optimization is the detailed investigation of the robustness loop.

Specification of Uncertainty

The special needs of early design stages are addressed by defining uncertainty or deviation values **r**. One module concept should fit into possibly every future car targeted by the module strategy. Therefore, those uncertainties can be relatively large. Nevertheless, four types of uncertainty influencing module development are identified [2]:

1. Uncertainties due to the car model validation process
2. Uncertainties due to early stage data availability
3. Uncertainties due to used CAD methods
4. Uncertainties due to innovative solutions for standard modules

Evaluation of Robustness

The development of standard modules is based on functional requirements. These are typically structured into requirements that *must* or *can* be fulfilled by the standard module. The robustness loop seeks to identify the relation between uncertainties and functional requirements.

First, uncertainties have to be derived according to the four presented types in early design stage. Second, the resulting robustness has to be determined. Therefore, statistical analysis needs to be done on the functional requirements. This means that output functions of functional requirements are analyzed based on failure probability, coefficient of variation, etc. Further methodological background and an example for early design stage problems can be found in [8].

Implications of Robustness Loop

In contrast to probabilistic RO, this approach does not strive to investigate solutions for standard modules concerning their feasibility for production or usage. E.g., failure probability is not minimized to a level of six sigma. Due to the large uncertainties of module integration, failures have to be accepted in the percent range in the course of ERO. This leads to an extension of functional requirements. On one hand, developers have to commit to considered statistical values of the functional requirement that *must* be fulfilled. On the other hand, there also has to be consensus about the weighting of these statistical values.

This step forces a very early and detailed discussion on functional requirements of all involved and affected by the investigated module. However, only the interdisciplinary commitment to the functional requirements extension enables users to judge the robustness of different solutions for standard modules. Thus, the technical applicability of this approach requires emphasis on frontloading of the car development process. This means that emphasis has to be on the very first stages of development regarding human and budgetary resources.

Optimization of Robustness

Typically, inventive or innovative solutions start with bad values for δ_R. The approach therefore optimizes the robustness of each investigated solution in order to base the decision over a standard module on best operating solutions.

Starting from the overall robustness $\delta_{R,1}(\mathbf{d_1} \in \mathbf{d}, \boldsymbol{r})$ of initial design parameters of the investigated solution for a standard module, stochastic optimization algorithms seek to find $\delta_{R,opt}(\mathbf{d_{opt}} \in \mathbf{d}, \boldsymbol{r})$ for each competing concept. $\delta_{R,opt}$ represents maximum robustness of each solution against early design stage uncertainties. Thus, the systematic robustness evaluation is done after every optimization step. Finally, the decision about the standard module can be based on optimized solutions concerning δ_R.

2.3 Automated Implementation

In practice, the application of the process as illustrated above is often too complex for automotive designers who spend most of their time with the integration of modules into a high amount of cars. Therefore, a tool called Robust Design Automation has been created to automate the optimization of robustness, see Figure 5.

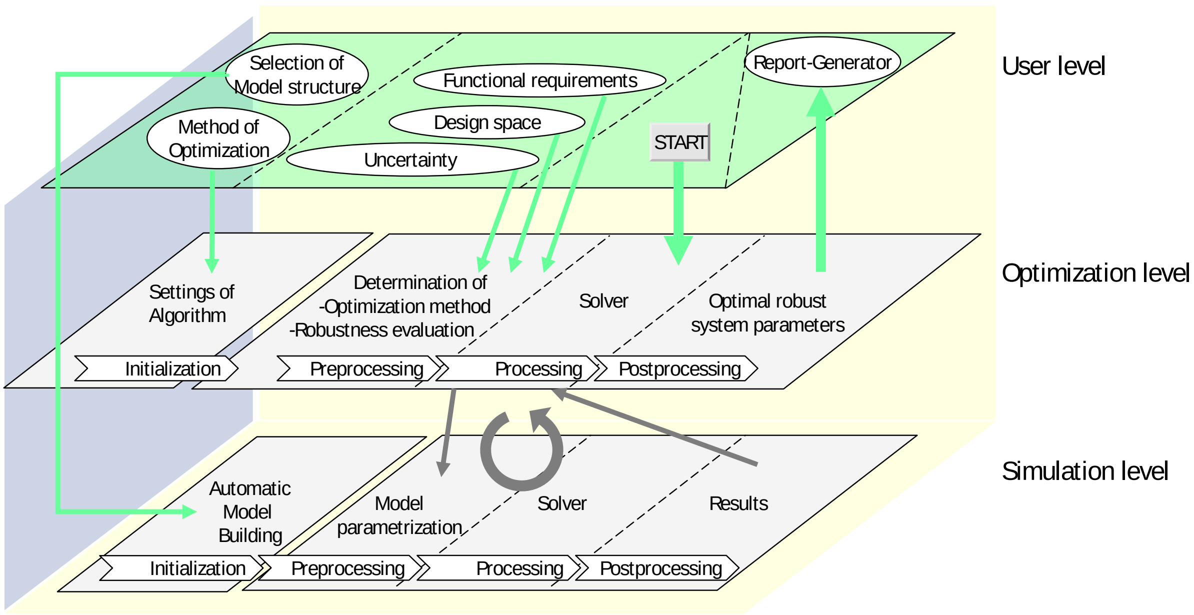

Figure 5. Process Flow of the Automation of ERO

Designers as users of the tool only have access to special parts of the process which are illustrated as green arrows. That means that they can change a few restricted settings of the optimization algorithm as well as the wanted model structure (e.g. different solutions for the standard module). Furthermore, users can modify the weighting and amount of functional requirements including statistical analysis. Functional requirements of automotive modules are typically derived from the company's strategy. Therefore, users can only weight or activate / deactivate functional requirements that are allowed by a tool admin familiar with the module strategy. Design space of concept models and uncertainties are additionally available for changes by the user. Subsequently, users press the Start-Button and the optimization process starts in a black box. Once optimization has finished, results are given in terms of a non-editable report. This report contains the user's settings, the optimal robust system parameters and a detailed justification why optimization chose the resulting parameters.

3 HUMAN INFLUENCE ON ROBUSTNESS

In practice, processes only work when the embedding of the technical process into the human framework of the product development process is taken into account. The introduced automation of ERO only considers robustness from the technical perspective. Therefore, the following chapter focuses on identifying interfaces between humans and the technical process. First, a model is presented to generate a main understanding of the investigated interfaces. The interfaces are structured into process demands and human requirements. Then, the automation of ERO is analyzed regarding the two types of interfaces.

3.1 Interface model

As shown in Figure 6, the technical process is embedded into a human framework. Within this framework, humans build the interface to and from the technical process. Seen on the left side, the process characteristics demand qualifications, A, of the users. Illustrated on the right side, users have requirements, B, on the process.

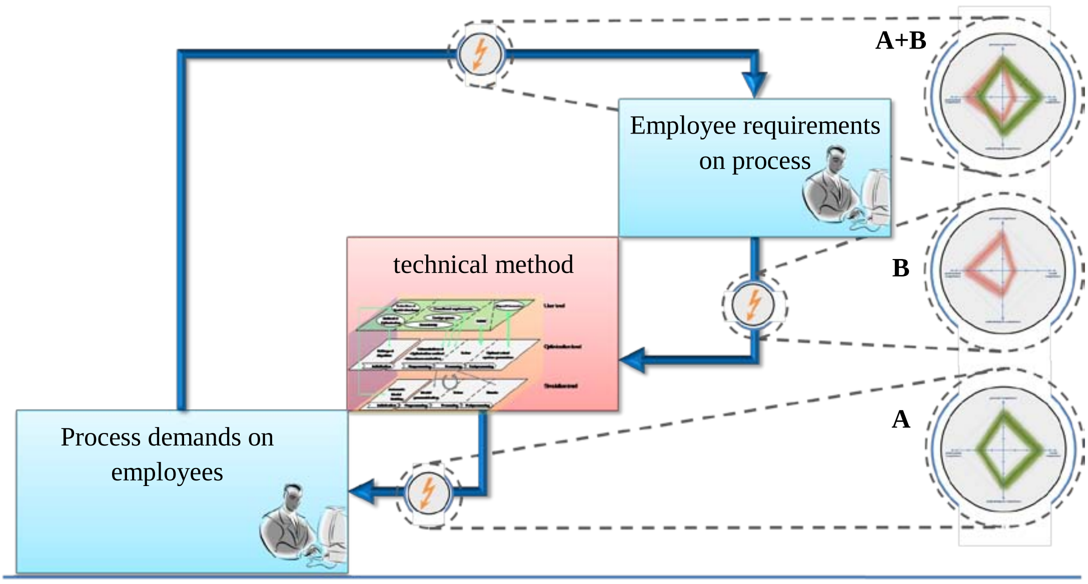

Figure 6. Interface Model

Optimal processes are characterized by congruence of both demand on designers and requirements on the process. Hence, the process robustness can be identified by the discrepancy between technical demands and human requirements A+B. This results in two ways of optimizing the process robustness. First, designers have to be qualified or selected according to the technical demands. Second, the process must be adapted in order to fit the designer's qualifications. The identification of process demands and human requirements is the first task of executives. Consequently, needs for action can be identified and have to be executed.

3.2 Technical Demands on Humans

The major business objectives like growth, profitability and innovation capability directly depend on the sum of a company's processes [9]. Because designers use processes, there is an indirect correlation between a company's success and the qualification of its designers. In the framework of developing ERO, emphasis is not on human uncertainties.

The following investigations mainly consider personnel risks due to suboptimal usage of human resources. Personnel risks for process robustness are here specified by weak performances concerning personnel recruitment, personnel placement and the chronological sequence of personnel development. Those factors directly determine the usability of a process [10].

According to Figure 7, the demands on designers can be structured into professional, methodological, social and personal competences. The proportions of these demands follow from the process environment, e.g. intercultural or interdisciplinary process characteristics.

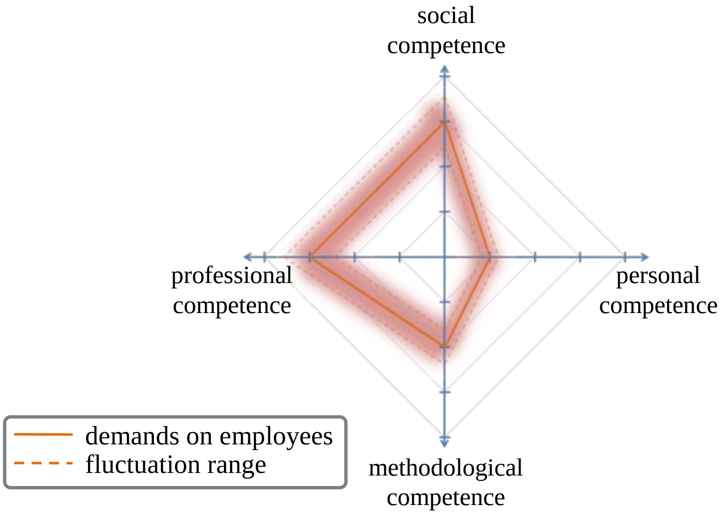

Figure 7. Demands on humans

Paragraph 2.2 shows the importance of frontloading as a fundament of ERO. Everyone involved in the module development has to participate in the extension of functional requirements. Depending on the global development strategy of the company, this might need a commitment of humans spread all over the world. Following, the demands on humans derived from frontloading are exemplarily illustrated.

In the context of frontloading, uncertainties have to be defined first. Therefore, all relevant uncertainties have to be identified. This demands specific know-how and experiences of participants in the field of the investigated module. Furthermore, the systematic identification and quantification of uncertainties requires a high methodological knowledge concerning statistical methods. However, the solitary emphasis on professional and methodological competences is not sufficient. E.g., the matching of the specific know-how of each participant demands social competences like persuasive power. All in all, interdisciplinary work is highly demanded from users of ERO. Hence, executives have to focus on designers with high social competences in addition to professional and methodological competences. Motivation is a key personal competence for success of ERO. But for the investigated aspect of frontloading, motivation does not play a major role for the frontloading aspect of ERO.

It can be concluded that the process robustness is driven by the designer's competences. By adapting all four fields of designer's competence to the process, executives have a major possibility to increase process robustness. This can be done both by selection or further qualification of designers.

3.3 Human Requirements on Technical Methods

The identification of technical demands on humans can be derived relatively easily, because the technical process determines the demanded human skills practically automatically. Unfortunately, the requirements of humans on the process can not be derived from the process. These requirements result from the diffuse mass of human developers. Currently there are no standards available characterizing the typical developer's requirements on a process in the automotive design process.

The identification of success factors has been topic of research in the field of project management. In this paper, an adaptation from project management to process management is proposed. Furthermore, this paper's contribution is validated by proving the proposal for the technical process of ERO in practice.

Research on success factors in the field of project management has been extended by Atkinson [11] in 1999. He included the customer's perspective by judging over the success of a project based on the customer's demands. Further research aimed at identifying so called critical success factors (CSF) of a project. Turner, Müller 2005 [12] and Spang, Eulert 2007 [13] proved the applicability of CSF by creating lists of success factors in different industries with specific cultural backgrounds.

Deepening the research on CSF, works like Morris and Hough [14], Fortune & White 2006 [15], deal with the description of interdependencies between the critical success factors. This enables a holistic view to evaluate the success of projects. The human being as a main part of CSF is characterized by its needs, interests, performance skills and willingness to perform. The output of human actions is everything that is produced directly or indirectly in the context of a working process. This output strongly correlates with the fulfillment of human requirements on projects.

Starting from these thoughts, the characterization of the human being is transformed to the process level. According to Müller [16], the relevant criteria of human needs that are valid for the process level are identified and clustered in Table 1.

Table 1. Human requirements on a process

Cluster	Characteristic of cluster on process level	Human requirements on process
C1	Plausibility of the process	- Reasonable task - Transparency - Confidence in the process - Target-oriented (regarding time, cost, quality)
C2	Compensation	- Pursuit micro politics
C3	Team's willingness to perform	- Work creatively - Be innovative - Play instinct - Usability of systems / tools - Standardization
C4	Working culture	- Bindingness of decisions - Commitment to execution - Failure culture (manner of handling failures)

The clusters shown in table 1 have been derived from project management. To provide a valid and consistent transformation from project management to process management, a qualitative survey has been conducted among project designers and process users of a luxury-segment OEM's development division.

Questions within each cluster have been prepared to find out the requirements each respondent demands on a process. Following, the interpretation of the survey's result are described. The survey is currently not finally completed. Hence, partial results of the survey are evaluated. Nevertheless, subsequent conclusions have been considered for the implementation of ERO and are illustrated in the following paragraph.

3.4 Human Requirements on ERO

3.4.1 Plausibility of the process

The first cluster describes the logic of the process from the designer's perspective. Here, the claim for the reasonable characteristic of a task has been identified as a success factor. This success factor is strongly linked to transparency. For the surveyed designers transparency of a working process is equivalent to understanding the procedure of reaching the target of the process. If the process provides for transparency, designers typically highly identify themselves with the process. In this way, they gain confidence in the process because the targets and the procedure to reach those targets are disclosed.

Consideration for ERO

In order to meet the requirements of C1, the automation of ERO contains a report generator. This report generator establishes the required transparency. All assumed inputs for the optimization process including technical uncertainties are taken into account. Furthermore, the decision about the optimal design parameters is proven by detailed technical diagrams that can be validated by real tests.

3.4.2 Compensation

Usually, the more time and energy designers invest in their specific project task, the better the result is. The designer's investment is driven by the pursuit of his working goal. Consequently, designers are satisfied when reaching the goal because they are able to identify this achievement as personal and common success. This success is usually evaluated and appreciated from the designer and his environment. Striving for the goal under time pressure typically causes the compensation of parallel tasks of users. Designers want to pursue micro politics, i.e. their personal goals in terms of career, etc. It can be concluded that a process has to ensure that users can pursue personal micro political targets parallel to their specific project task.

Consideration in ERO

The standardized process of ERO enables process users to reduce manual calculation that has to be done over and over again. Rather, designers can put more emphasis on conceptual work that might result in filing patents. This results in working towards personal goals like appreciation from the management or monetary compensation

3.4.3Team's Willingness to Perform

The team's or designer's willingness to perform is mainly dependent on their motivation. Motivation is usually structured into intrinsic and extrinsic motivation. In opposite to extrinsic motivation, intrinsic motivation cannot be influenced or manipulated by the process. Therefore, a process should strive to increase extrinsic motivation. According to the current results of the survey, each process should cope with the claim for innovative and creative working. Especially in development departments, there is a high demand for allowing a so called ‘play instinct’. This typically can only be provided when developers can ‘play’ within a standardized process.

Consideration in ERO

ERO describes a clear framework how arbitrary concept solutions can be taken into account during early design stages. Therefore, users of ERO can pursue and evaluate every solution for standard modules. As stated in C2, designers are able to do more conceptual work. This directly supports the development of the designer's creativity. Additionally, the automation of ERO is implemented regarding its ability to work for all automotive modules combined with a high usability. The working processes of users are hereby embedded into a standardized process.

3.4.4Working Culture

In context of the conducted survey, one of the most frequent answers aim at the volatility and missing support of management decisions during development. Furthermore, respondents complained about the suboptimal handling of failures from the designer's perception. This means that failures seem not to be accepted by the management. Thus, failures are not used as a chance to improve processes. Eventually, designers experience a working culture where they try to be perfect workers that never make mistakes.

Consideration in ERO

The frontloading aspect of ERO forces all involved designers and the management to an early analysis of potential failures in terms of uncertainties that occur during the development. This leads to a common commitment of the input for ERO. Therefore, everyone involved is responsible for the results of ERO. This simultaneously leads to a change of the designer's role. Users of ERO do not have to judge over uncertainties during the process. Instead, their main task is to provide for plausibility of the results by validating simulation outputs.

Furthermore, the parallel pursuit of different solutions for standard modules makes it possible to investigate very innovative or inventive concepts. Without ERO, those would have been refused in an early stage by external pressure (colleagues, management). By supporting innovation, ERO has the potential to change the development division's attitude with unconventional ideas and their potentials.

4 CONCLUSION

Implying the high complexity of module based car development, this paper deals with methodologies to increase the robustness of standard modules. Different solutions for standard modules are consolidated during the earliest stages of car development. The presented method Early Robustness Optimization (ERO) seeks to optimize the robustness of conventional and innovative solutions. Following, the automated optimization in terms of implementation of ERO is embedded into car development. Whereas technical robustness of standard modules can be achieved by ERO, humans as users of ERO have a huge influence on the actual achievable robustness. To investigate the human influence, an interface model is generated. This model distinguishes the demands of a process on humans from the requirements of humans on a process. Whereas an arbitrary process relatively clearly determines the demands on humans, the human requirements on a process can not be derived from the process. Therefore, the critical success factors are transformed from the perspective of project management to process management based on surveys among designers. The automated process of ERO has been developed regarding the identified critical success factors. Those factors are currently described qualitatively. In order to be feasible from the management's view, the transformation from qualitative description to quantitative determination has to be investigated during the use of ERO as a part of the car development process. Then, the discrepancy between technical demands and human requirements can be quantified. The management's task based upon is to minimize the identified discrepancy. This optimizes the process robustness and consequently the overall robustness of the automotive module.

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