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STRATEGIES AND PRINCIPLES TO DESIGN ROBUST PRODUCTS

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1. Introduction

Today, many products do not completely fulfill the expectations of the users. This might be caused by the deviation of product properties due to variations within the production processes. However, a more significant reason is, that certain wishes of some users are not taken into consideration within development. A typical example is the use of a product under environmental effects it has not been designed for. Even products, which have been successful and approved, might possess a not-satisfying behaviour in this case. Dealing with load-carrying systems, this can even lead to damages of the structure and possibly to a failure of the system.
Summing up the presented phenomena and their causes, they can be considered as uncertainties. Within the CRC 805 "Control of Uncertainty of Load Carrying Systems in Mechanical Engineering" at the Technische Universität Darmstadt the origin, causes and effects of uncertainties are explored. It is the aim of the CRC to develop comprehensive methodologies for the controlling of uncertainties. For this reason, not only mathematical procedures but also mechanical engineering procedures, as well as models and methods for describing, modeling and analysing of uncertainties are developed. Based upon this, optimisation procedures as well as methodologies regarding the design of products and processes for the synthesis of robust products and robust processes are elaborated. Here, the systematic design of robust products and robust processes, called Robust Design (RD), is an essential part. The matter of this paper are the early phases of product design within the new-development of robust products with regard to the use of the product. The design of robust production processes is to be examined later on.
In the following, products are called "robust" if uncertainties, which occur in every product life cycle process, do not affect the behaviour of the product. They fulfill the expectations of the customer also in regard to changing requirements and altered environmental effects, e.g. dealing with changed or new use processes.
An optimal robustness can only be reached, if the product is designed completely robust and all-embracing from the beginning of the design. Therefore, the RD targets particularly the new-development of products, since here the most comprehensive influences for the generation of product properties exist. The designer is able to optimise the robustness from the beginning by choosing adequate functions structures, effects, principles and embodiment. The best way is to develop robust products in a systematic RD-development process. Basic elements of such a RD-process are comprehensive systematically structured strategies and tools. The tools provide effective instructions in the form of principles, guidelines and examples for the targeted decrease of effects caused by uncertainties. This decrease is achieved by design measures. The tools also contain typical solutions and examples. In order to support the design of robust products from the beginning, the tools have to

be provided for each product model of the different levels of concretion. In this paper, a comprehensive concept of a methodology for the design of robust products is presented.

2. RD-Methodology Concept

The concept of the RD-methodology contains the description of a methodic procedure with the systematic use of models, methods and tools. The procedure is primarily supported by a scheme for the systematically structured supply of RD-tools:

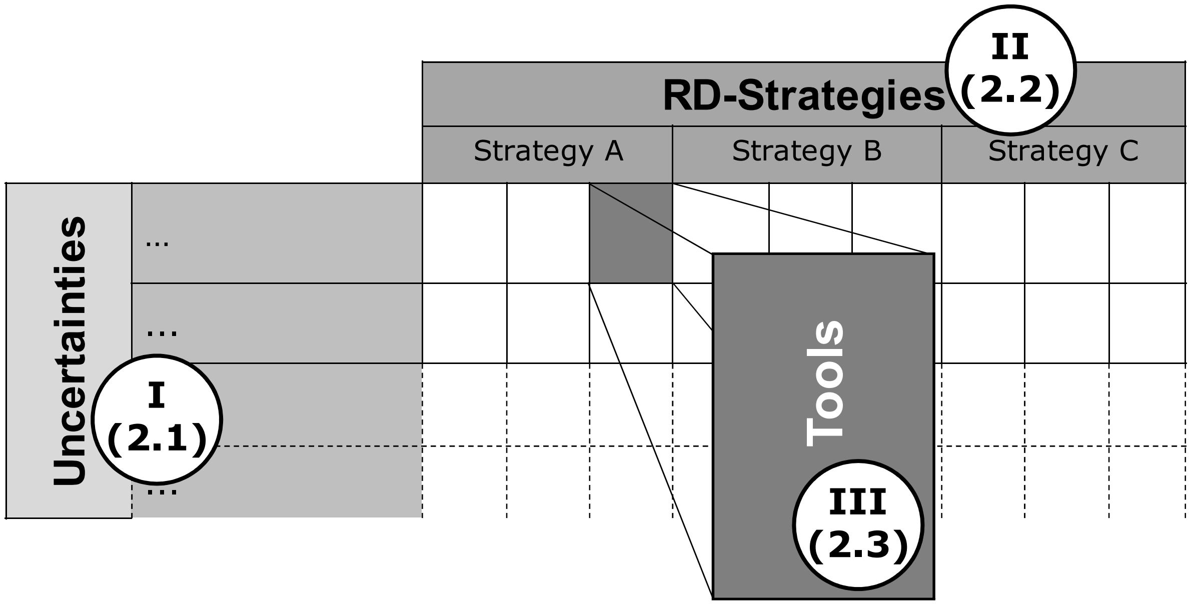


Figure 1. Methodology concept of RD

This scheme is built up basically on three elements: At first, one acts on the assumption, that adapted solution approaches have to be provided for each kind of the different uncertainties (I). For example, uncertainties in the form of disturbances require other measures than uncertainties, which might arise due to a changed product behaviour caused by wear.

Furthermore, one acts on the assumption, that different solution approaches for the controlling of uncertainties are possible depending on the product type, appliance and environment. In order to structure these clear arranged and comprehensible, superior strategies are devised, how uncertainties can basically be controlled (II). The allocated tools are dedicated to these strategies (III). In addition, the solution approaches are structured in regard to different concrete product models, so that the approaches can be chosen precisely within all phases.

Based on this scheme, procedures and methods are devised, which enable the identification and the classification of relevant uncertainties and support the selection of a purposeful effective RD-strategy, which leads to the desired result. The tools are structured as well, orientated towards engineering-design-methodical categories, in order to give the designer an as concrete as possible support when dealing with different problems.

The three elements of the scheme are explicated in detail now:

2.1 Uncertainties (I)

Uncertainties arise, when product or process properties cannot be determined [Engelhardt 2009]. The deviation of the property of target- or expected value and their statistical distribution is called uncertainty. Here, the eventually observed deviations of the properties as well as the causing influences and effects are considered as uncertainties. The examination of the uncertainties includes the measurable product properties, the behaviour of the product in use processes, the costs and delivery times. If one considers, that the product properties and the product costs are determined by the necessary production processes for the fabrication of the product, it is obvious, that the examination of uncertainties can only be carried out based on a process modeling [Kloberdanz 2009]. Thus, the analysis of the occurring uncertainties can happen with the help of a process model:

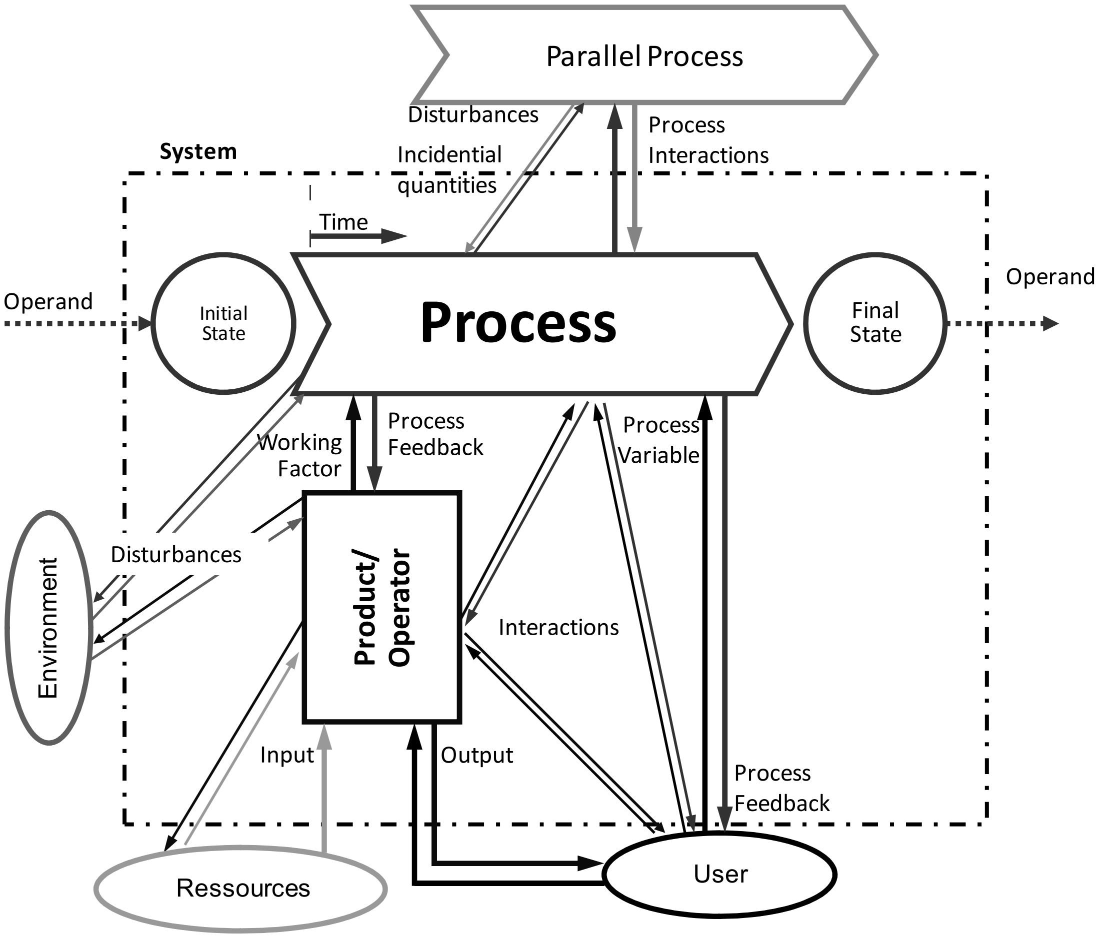


Figure 2. Process model to model processes and analyse uncertainties [Kloberdanz 2009]

In this model of technical processes the interaction of operand, resources, environment and operator for the accomplishment of a process is illustrated. The process describes the temporal change in state of an operand. Operands can be either objective operands (e.g. material, workpiece) or non-objective operands (e.g. information). The operand itself is in interaction with other processes. There is an intended or unintended interdependency between all elements of the process model. Now, it is assumed, that all elements and all interdependencies are subjected to deviations.

Based on this model, uncertainties can be classified, exceeding the possibility of a complete analysis. Very typical is the deviation of the intended input parameter, in particular the one of the resources or the operand and the occurrence or increasing of unintended disturbances. For example, an uncertainty of the resources might be a variation of the energy supply or the yielding of the fundament when working with machine tools. Typical disturbances would be temperature, pollution or corrosion through ambient media. Here, one has to consider, that generally one is dealing with interactions and therefore, for example, attention has also be paid to the unintended effects of the product or process upon the environment and operator as well. For instance, emissions or user impacts can posses a not acceptable extent.

Within this paper, only disturbances from the environment, which affect the product and the possible tools of the RD are taken into consideration. These developed structures are transferred to further uncertainties later on. Moreover, further adequate tools are added and by this, the scheme and methods extended.

2.2 RD-Strategies (II)

Within corresponding literature versatile instructions are known, how to realise or design products, so that they work independently from influences of disturbances safely and reliably. For example, Pahl describes this very elaborately and systematically in regard to basic principles [Pahl 2007] and Anderson uses these basic principles for RD [Anderson 1997]. Here, advice for typical products of mechanical engineering are given in particular. However, these approaches are limited to special product groups and to the avoiding of impacts from disturbances within the embodiment phase through measures regarding the designing. Additionally, the access to the mentioned advice is hindered by the fact that they are examined from the view of common product embodiment and therefore are integrated in a great amount of general design principles and rules. Another example of intensive but special work with occurring uncertainties are the advice for the electromagnetic compatibility (EMC) [Schwab 2007]. Furthermore, interesting approaches for the examination from the view of the RD are known [Jugulum 2007]. These, as well, are limited to special kinds of products. Additionally, one deals here with an approach, which orientates itself strongly empirical close to TRIZ.

On the contrary to this, a comprehensive as possible system of tools is developed now, which is founded from the view of the RD and structured systematically. By this, the tools for RD are supposed to become applicable as generally as possible and easy to access. The structure orientates itself with the basic criteria of physics and the system engineering. By this, the system can be extended without any problems.

For the structuring it is necessary to define superior criteria. For this purpose, strategies are devised, how to develop technical systems so that they are generally robust against disturbances.

The basis is formed by the character of the disturbances. It can be modeled adequately:

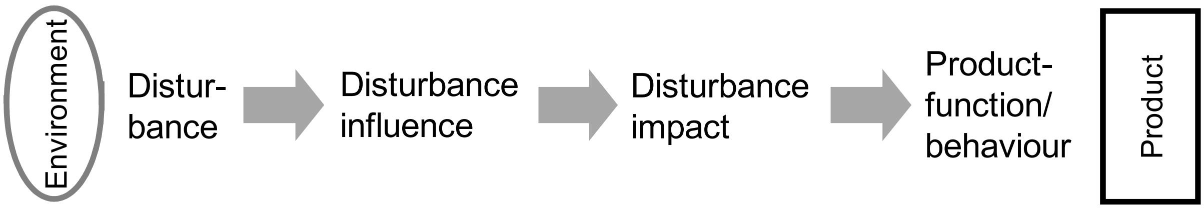


Figure 3. Model of connection between disturbances and product function / behaviour

- **Disturbance** result from the product and process environment. Typical examples are the temperature, humidity or dirt.
- Disturbances can influence the product in different ways (**Disturbance influence**). A typical influence of the temperature is the warming through convection or radiation. A high humidity can cause maceration, a low humidity can lead to a drying-out. Dirt can sediment on the surface of the product or get in the pairs of effective surfaces of the product.
- The influences of the disturbances can have different impacts upon the product (**Disturbance impact**). The impact of the disturbance depends on the sensitivity of the product against the influences of the disturbances. Thus, it might occur that an influence of a disturbance does not have any impact upon the product (at least within large codomains). Typical examples are solid-lubricated mechanical products, which can also be used under extreme temperatures. Likewise, a disturbance can have a fatal effect upon the function of the product or its behaviour. For example, fine mechanical machines fail comparatively quickly when they are exposed to dust or dirt without protection.

Based upon this model three RD-strategies can be derived directly:

- Eliminate disturbance
- Reduce / eliminate disturbance influence
- Reduce / eliminate disturbance impact

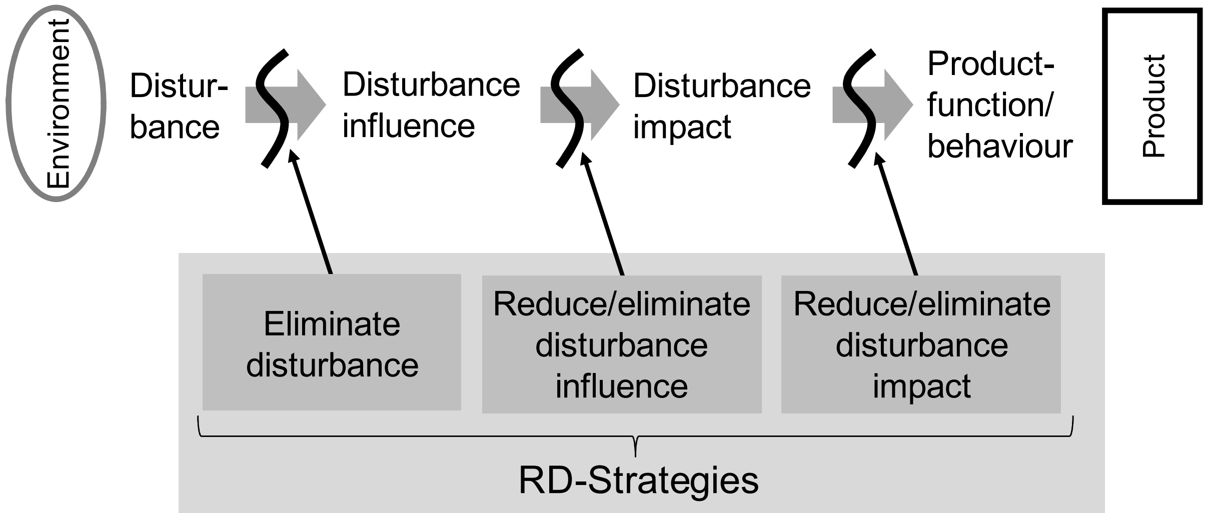


Figure 4. The three RD-Strategies

The strategies are no arbitrary independent alternatives, but they are built on each other.

The strategy **"Eliminate disturbance"** acts on the assumption, that the according disturbances do not appear in the system environment or do not appear in such an amount, so that they would cause a disturbing influence or impact upon the system. For this, the system environment has to be defined specially. Examples are conditioned measuring rooms, in which high-precision measuring instruments are used or clean rooms for the production of data mediums.

This strategy is connected to a limitation of the application range. In fact, this strategy is a very easy solution from the view of product development. However, it is not acceptable for many products in its entirely.

The strategy **"Reduce / eliminate disturbance influence"** acts on the assumption, that the existence of the disturbances is accepted, but the influence of the disturbance upon the product or parts of the product is reduced or eliminated. Normally, extra measures are necessary, which "interrupt" the influence of the disturbances. For example, when dealing with the influence of temperature through convection from the environment a heat insulation can be installed. In order to prevent dirt from getting into the product, proofed cases can be used.

At this strategy, besides these uncertainties physical and chemical effects, on which the influence of disturbances is based on, have to be considered as well. For instance, when dealing with solar radiation, reflectors (radiation protection sheet) reduces the influence of the disturbance more effectively than a (black) insulating layer. However, the reflectors are more or less useless when dealing with convection.

The strategy **"Reduce / eliminate disturbance impact"** acts on the assumption, that the existence of a disturbance and its influence is accepted, but the product is planned and designed in such a way, so that the influence of the disturbance does not unfold a harmful impact. For example, typical products of mechanical engineering can be designed suitable for expansion, so that heat expansion due to the influence of temperature does not affect the function or behaviour of the product. In general, such measures do not require additional parts, but have to be considered within the early design phases and can limit the choice of solution possibilities. The examination has to exceed the physical or chemical connections. Additionally, the harmful impacts upon the product and upon the executed process have to be considered. For instance, the warming of a mechanical part can lead to the expansion of the part but additionally to a decrease of the strength and rigidity value or the ability of lubricants. A differentiated examination is for example also necessary, when parts are warmed fractional (not entirely) and an uncontrolled forming (distortion due to heat) occurs. The choice of a material with high heat conductivity can be adverse for the total expansion of the part.

When applying the strategies it has to be taken into consideration that the strategies posses certain limits in which they are effective in unequal ways. By this, a prioritisation results between the strategies:

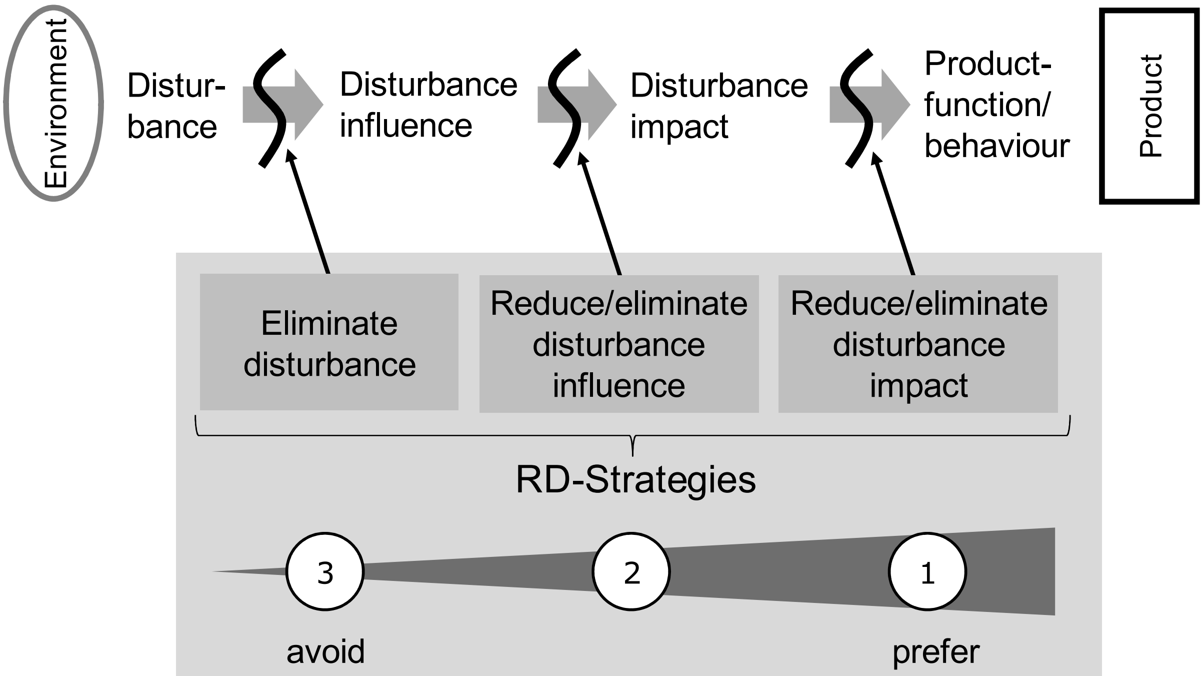


Figure 5. Prioritisation of the RD-Strategies

- The elimination of disturbances, their influences and impacts is not always possible. In many cases, a reducing is satisfactory. Here it has to be evaluated, when a damaging or not-acceptable impact occurs.
- The strategy of reduction or elimination of impacts should be preferred to the decrease of the influence if possible. The elimination of disturbances should be considered as the last alternative or as a supporting strategy. The strategy for the decrease of the influences of disturbances requires design measures, which generally leads to extra effort. However, generally this is seen more noncritical by the customers than a limitation of the use, which results from the elimination of disturbances.
- The strategies are not clearly separated from each other. For instance, the impact of a temperature influence can be reduced by an integrated tempering of the product (cooling or heating). This measure does not reduce the influence of the temperature and therefore has the character of an impact-reduction. However, this measure also has the character of an influence-reduction, since it requires additional components. In the end, the strict allocation is less important than the finding of the solution approaches.

At the description of the strategies and at the explicating examples only influences from the environment upon the product were examined. The explanation is correspondingly valid for the opposite way – the emission from the product to the environment. In addition, here it is a general rule to plan and design the product in such a way, so that damaging emissions are not even created. The second best solution is to reduce or eliminate the influence from the emission upon the environment. Generally, the reduction of the influence upon the environment has to occur within the product and therefore additional components are necessary. The use in an environment, in which emissions can be accepted, will generally limit the appliance of the product.

2.3 RD-Tools (III)

The structured disturbances and strategies form such an outline, which enables the extensibility and an effective access to the tools for the controlling of disturbances. The tools are here the real support for the designer in RD. However, in order to allow a general applicability, no direct solutions are given for a concrete problem or concrete product. Therefore, the tools can only be provided in a kind of catalogue and offer only example approaches which present the principle solution. Furthermore, the main factor of success of the tools is based upon their structure, which has to support the efficient access and the flexible extensibility. Therefore, the configuration of the documents and the outline of the contents have to be examined in detail. The tools have to be arranged coherently for the designer and they have to support the understandings of the relations at robust products. It appears that an individual catalogue-system can be generated for each one of the three RD-strategies. Similar to the RD-strategies, the catalogue systems are based on each other. Generally, the configuration of the catalogue orientates itself towards the configuration of design catalogues. At first, the entire content is structured by classifying criteria. The criteria should be chosen as general as possible in order ensure, that the catalogue is complete and free of any redundancy. The criteria of the outline take natural scientific quantities as a basis. For mechanical engineering systems the physical quantities are important. In order to maintain a better clearness, the electrical quantities are listed separately. Chemical quantities can play a major role concerning corrosion. Biological quantities, like mildew, have to be considered also.

2.3.1 Tools for the RD-strategy "Eliminate disturbance"

In order to eliminate harmful disturbances it is necessary to identify them. Thus, the knowing of the possible disturbances is decisive for the RD. On the one hand, one problem is not to miss any disturbances and on the other hand to identify the relevant disturbances from the large amount of potential disturbances. Both is supported by the applying of the process model (2.1).

Clasifying criteria			**Disturbances**		**Relevance**			
Physical quantities			**Notation of disturbance**	**Example**	Environment specific	Utilisation specific	Product specific	…
	Material							
		• Solid	Pollution from dust	Waer of bearings				
			Blocking by foreign particle	…				
			Abrasion	…				
			…					
		• Liquid	Cavitation	Abrasion of material in a turbine				
			…					
		• Gas	Variation of density	…				
			Condensation	Short-circuit in electronic unit				
			…					
	Field quantities							
		• Temperature	High temperature	Stick of bearing				
			Low temperature	Slip of friction force joint connection				
			Variation of temperature	Untighten of conic connection				
			…					
		• Magnet. Field	…					
		• …						
Electric quantities								
	…							
Chemical quantities								
		• …	…					
Biological quantities								
…			…					

Figure 6. Tool catalogue for the RD-strategy "Eliminate disturbance"

Every physical quantity can be allocated to several disturbances. For instance, when dealing with temperatures it is interesting to examine high and low temperatures as well as the variation of temperature. For a better and quicker understanding, an example for a disturbance, which can be related to influences or impacts of disturbances, is presented in every case.

Within this strategy the measures are reduced to the defining of the environment in which the according product can be used. For this purpose, the identified disturbances are examined and stated relevant to the complied values for the particular quantity.
The evaluation of the relevance of each particular disturbance is supported by a kind of solution characteristics in the catalogue. Here, information regarding the typical connections between disturbances and products or product groups is given. The information is outlined according to specific environments, appliances and products. The columns can also be used in order to identify the relevant disturbances, if the catalogue is arranged in such a way. These solution characteristics are used in similar form within the other two strategies.

2.3.2 Tools for the RD-strategy "Reduce / eliminate disturbance influence"

For the elimination or reduction of influences of disturbances many tools can be used. There is a multitude of more or less effective tools, written in general or specialized literature, for the controlling of the influences of disturbances. In regard to the influences it is decisively, to examine the effects, which are the cause of the influence. Often, these effects can be described with mathematical equations or graphical illustrations. In order to enable a quick understanding of the influence, examples are given here as well.

Disturbances	Influence of disturbances			Measures / solutions		Relevance			
Notation of disturbance	Effect	Equation / graphical illustration	Example	Rules, principles, instructions	Solution examples	Environment specific	Utilisation specific	Product specific	…
High temperature	Radiation	$\dot{Q}_{12} = \varepsilon_{12} A_1 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]$	Solar radiation	Small ε	Reflection sheet, white colour				
	Convection	$\dot{Q} = \alpha A (T_w - T_\infty)$	Heat of exhaust air	Small α, distance, cooling of surface	Flow control sheet, water-cooling under surface				
	…								
Low temperature	…								
Variation of temperature	…								
…									

Figure 7. Tool catalogue for the RD-strategy "Reduce / eliminate disturbance influence"

Obvious points of action result often from the equations of the effects, but also there are other points coming up from experience and known solutions. For theses points according rules, principles and information can be stated. Now based upon these, the designer has to derive and realise special measures for his product, in order to define it robust against the examined influences of disturbances. For example, a high temperature, as a disturbance, can posses an influence in form of radiation. Now, it is attempted to reduce the influence by applying a small ε. For instance, this is often realized by placing reflection sheets between the radiation source and the product or parts of the product. By this, a larger part of the radiation does not have any influence upon the product anymore.
Measures, which are effective against one influence, can thoroughly be of support dealing with other influences. However, this connection is not ensured and is not easy to overlook. For example, sheets for the reflection of radiation provide no effective protection from convection, if they are not designed optimized regarding the flow. Therefore, it is firstly necessary to examine each influence separately and to derive according measures. Afterwards, it is possible to detect synergy effects between the measures and to realise these together effectively.

2.3.3 Tools for the RD-strategy "Reduce / eliminate disturbance impact"

Similar to the previous strategy, there exist multi-sided tools within literature for the elimination or reduction of the impact of disturbances. An impact can also be described by the effect with an equation or a graphical illustration. However, it is decisively, that effects describe the impact upon the product and not the influence of the disturbance. Nevertheless, the effects are supposed to represent possible impacts as general as possible. For this reason, typical effects are listed here, which occur often and lead often to known failures. Examples are given again as well.

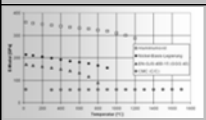
Disturbances	Impact of disturbances			Measures / solutions		Relevance			
Notation of disturbance	Effect	Equation / graphical illustration	Example	Rules, principles, instructions	Solution examples	Environment specific	Utilisation specific	Product specific	…
High temperature	Heat expansion	$\Delta l = l_0 \alpha \Delta T$	Iron bridge in the sun	Design to allow expansion	Fix-loose-bearing				
				Small α	Invar-material				
				…					
	Distortion	$\Delta l_1 \neq \Delta l_2$ $l_1 \alpha \Delta T \neq l_2 \alpha \Delta T$	Machine tool without portal structure	Symmetry					
				Heat com-pensations	Heat of one side				
				…					
	Change of young's modulus		…	…					
	…								

Figure 8. Tool catalogue for the RD-strategy "Reduce / eliminate disturbance impact"

A larger amount of impacts upon a component results from a high temperature. There are several possibilities for the elimination or reduction for each impact. For instance, a thermal expansion can be caused by a high temperature. This expansion can be reduced by the guideline "Design to allow expansion". A much known example for the appliance of this guideline is the designing of a fix-loose-bearing. Furthermore, one can try to eliminate the disturbance by applying a small thermal expansion coefficient α. A known way within this approach is the use of the material Invar.
A further impact of high temperatures can be distortion, where a component expands unequally on both sides ($\Delta l_1 \neq \Delta l_2$). For example, realising a symmetric design can be used in order to encounter this impact of the disturbance "high temperature". Resulting from the instruction, that a symmetric design can control this uncertainty, the designer has to derive according measures and design accordingly the component symmetric. After the measure was implemented, the disturbance has no longer the impact in form of distortion upon the component.

3. Summary and future work

This paper lines out the configuration of an all-embracing, systematically structured system of uncertainties, strategies and tools, which recommend the constructive solution possibilities within the RD and enable an effective access. The system was elaborated elementarily and its ability was proven through exemplary applications. Furthermore, it is the aim, to extend the system to achieve a complete catalogue for the support of RD. The applicability is going to be shown with exemplary developments. Up to now, only mechanical engineering products and embodiment solutions have been discussed due to the clearness. In following research an extension is planned, to include product models of the early development phase as well.
Additionally, the illustrated system was presented in a paper-based form. However, it is obvious, that in the following a larger amount of data is going to be accumulated so that it cannot be handled in paper-form effectively. Also, the easy use is going to be a decisive factor of success for the appliance of the system within RD. Due to the larger complexity and the multi-sided and complex connections, a flexible, computer-based version of the catalogues is going to be inevitable in future. However, due to

the clear outline, good conditions have been established for the computer-implementation. The clear configuration and outline support future additions and extensions.

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