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SET-BASED PRODUCT DEVELOPMENT IN THE MANUFACTURING INDUSTRY

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1. Introduction

The continuing globalization leads to a high product variety and a massive price pressure and thus presents a major challenge for manufacturing companies [Schuh et al. 2012]. To address these challenges by a unique positioning in the market and to meet customers' needs, an efficient realization of development projects is necessary [Schuh et al. 2012], [Fröndhoff et al. 2013], [Feldhusen and Grote 2013]. Therefore companies typically specify a product design solution in the early phase of the development process, even though this is the project phase with the highest uncertainty concerning information quality and the highest decision importance in a product development process [Lenders 2009]. But, the determined product design solution often turns out to be insufficient with regard to customer needs, product performance and/or product costs. This leads to product adjustments and iterations in the late project progression [Smith 2007].

One existing alternative approach to increase the efficiency and effectiveness of development projects is set-based design. In contrast to the determination of the product design solution in an early phase of the development project, so called point-based design, the set-based design approach is characterized by a continuous development of several alternative product design solutions in parallel and thus the postponement of the decision regarding the used product solution to later phases [Ward et al. 1995], [Smith 2007], [Schuh 2013]. Although studies have identified advantages of set-based design, the method has not become an industrial standard yet [Bhattacharya et al. 1998], [Pahl et al. 2005], [Lindemann 2007].

Thus, the objective of the paper is to present an approach for set-based design which focuses on the evaluation of the project specific design solution principles and the interrelations of the solution principles within the design space. Based on the interrelations of the solution principles within the design space and the existing level of uncertainty the reduction potential of a parallel development of product design solution alternatives is derived.

The paper proceeds as follows. In the second section related work concerning set-based design and the status quo of the industrial application of set-based design is presented. In the third chapter a concept for the application of set-based design in the industry is explained. The paper ends with a conclusion and a description of the future work.

2. Related work

As the introduction shows, there is demand for an efficient realization of product development projects. To address this deficit the principles of set-based design as well as the status quo of the application of set-based design in the manufacturing industry are presented below.

2.1 Principles of set-based design

The product development process (PDP) is analyzed for years by researchers with the aim to continuously increase its efficiency and effectiveness. The stage gate process, structuring the development process into defined steps, [Cooper 1993] as well as the simultaneous engineering [Allen 1990] are two examples for developed approaches with a great impact on development time, quality and costs [Machado 2013]. Among these examples there are still big improvements in this field of research occurring. One interesting methodology for further improvements of the product development process is set-based design firstly, described by Ward, Liker, Christiano and Sobek [Ward et al. 1995].

The basic idea of set-based design is to increase the efficiency and effectiveness of development projects due to the avoidance of iterations and problems in later project phases caused by a too early determination of the product design solution. These iterations and problems, especially in late project phases, lead to higher costs compared to a parallel development of different alternative product design solutions and a systematic reduction of product design solution alternatives along the project progress [Ward et al. 1995], [Bhattacharya et al. 1998], [Pahl et al. 2005], [Nehuis et al. 2012].

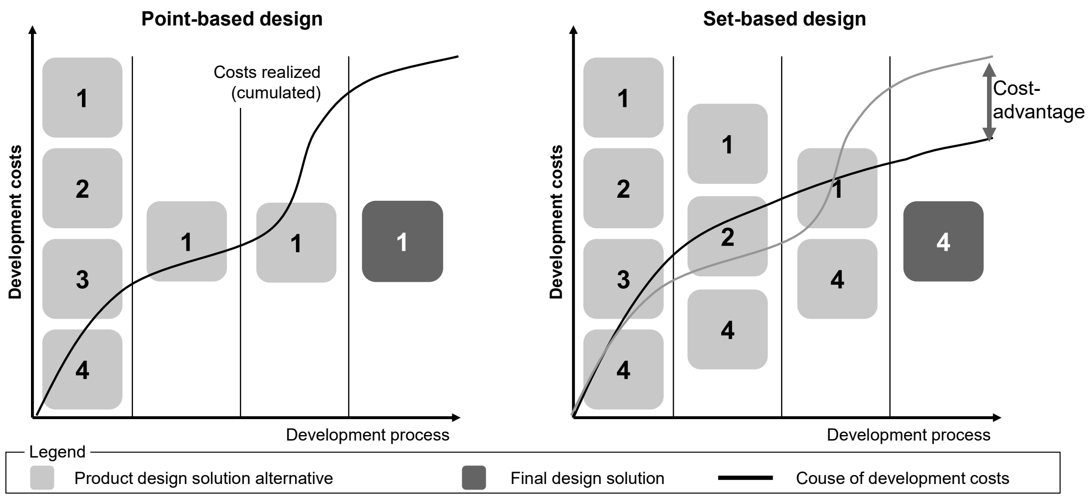

Figure 1. Comparison of point-based (left) and set-based design (right) [Lenders 2009], [Nehuis 2012]

Considering the relevant literature the existing approaches dealing with set-based design can be divided into general and methodological approaches. The general set-based design approaches discuss the basic idea and the basic principles of set-based design, without explaining in which subsystem of the product a parallel development of product design solution alternative is useful and how to identify the "attractive" product design solution principles [Ward et al. 1995], [Kennedy 2003], [Morgan et al. 2006], [Smith 2007], [Lindemann 2007]. The existing methodological approaches in the field of set-based design are not taking the possible product design solution alternatives and their interactions into account. Furthermore, no systematic methodology for the convergence of the design space is described [Finch and Ward 1997], [Bhattacharya 1998], [Ding and Eliashberg 2002], [Morgan et al. 2006], [Madhavan et al. 2008], [Lenders 2009], [Malak et al. 2009], [Inoue et al. 2010], [Qureshi et al. 2010], [Canbaz et al. 2011], [Yannou et al. 2013], [Qureshi et al. 2014].

As a result, the quality of decisions within an application of set-based design in the industry depends on the involved people and the collaboration between technical experts and managers. This is cost and time intensive and therefore inefficient. Hence, a method for the application of the set-based design principle from a practical point of view is missing. Therefore, the status quo of the application in the industry has to be analyzed and the implications for a methodological approach have to be derived.

2.2 Industrial application of set-based design

With regard to the application of set-based design the results of a conducted industry survey shows that in the manufacturing industry a systematic implementation of the method is still missing. Across the analyzed branches "automotive OEMs", "automotive supplier", "machinery manufacturer", "component manufacturer" and "others" a parallel development without a systematic alternative reduction process can be identified as standard. The majority of the component manufacturers and of automotive suppliers for example have not embedded the parallel development of product solution alternatives in their product development processes yet. Although the majority of the automotive OEMs and the manufacturing industry have a parallel development of product alternative solutions partially it lacks of a clearly defined process for the reduction of the alternative solutions. Furthermore, the industry survey showed that the application of set-based design has positive effects on the key performance criteria project time, project costs and product quality [Schuh et al. 2015]. Thus, the parallel development of product design solution alternatives is an interesting method to further improve the performance of a company's product development

3. Method for operationalization of set-based product development

For the implementation of set-based design within a product development project the description and transparent representation of the design space is the first challenge. Therefore, the sub functions of the product or development object and the available alternative design solution principles have to be identified. The resulting variety of product design alternative solutions has to be mapped systematically. Based on the structured design space a detailed consideration of the solution principles is necessary. Therefore, the level of uncertainty of the solution principles is evaluated. For the assessment of the uncertainty existing method for uncertainty analysis are adapted for the application in the early phase of a product development project. In addition to the evaluation of the uncertainty of the solution principles the interactions and interdependencies of the solution principles in the context of the design space have to be derived in order to determine the further developed product design solution alternatives. The following sections contain the detailed description of each step of the concept for the application of set-based design in product development projects. The presented method is based on experience in research and industry projects within the field of innovation management. Within a research project the understanding and interpretation of Set-based design as well as the derived sub-models of the approach are continuously discussed with the nine involved companies. The second activity which is contributing the study is the validation of the developed approach within a working group. The working group, established in January of 2008, contains of eleven companies of the manufacturing industry from Germany, Austria and Switzerland (DACH countries) and serves as a platform for the further development of lean innovation in close cooperation between research and industry. Within this working group the method has been discussed and has been validated with one work group member.

3.1 Determination of the design space

For an application of set-based design in an industrial product development project the determination and visualization of the possible product design solution alternatives is the first step. For the visualization of the variety of product design solution alternative the product design solution alternative tree is used.

The main purpose of the product design solution alternative tree is the creation of transparency about the possible variety design solution alternatives in order to fulfil the targets of the development project. On the one hand, the tree structure enables firms to create a high level of transparency regarding their current development alternatives. On the other hand the structure helps the development team by systematically identifying all relevant product functionalities. In addition the resulting high level of transparency is an important input for the selection of the product design alternatives.

Within the product design solution alternative tree each product solution alternative is distinguished by its characteristic specification which is described by its "functionalities" and their respective "solution principles". Thus, the product solution alternative tree systematically displays all possible product solutions which can be chosen by the project management.

For the realization of the product solution alternative tree the relevant product functionalities and their respective options have to be identified. Based on the identified options for the relevant product functionalities the restrictions for the combination of these options has to be determined in order to identify which combination of options are allowed and which are forbidden. The resulting combinations of options according to the previously defined combination rules are representing the product solution alternatives (see Figure 2).

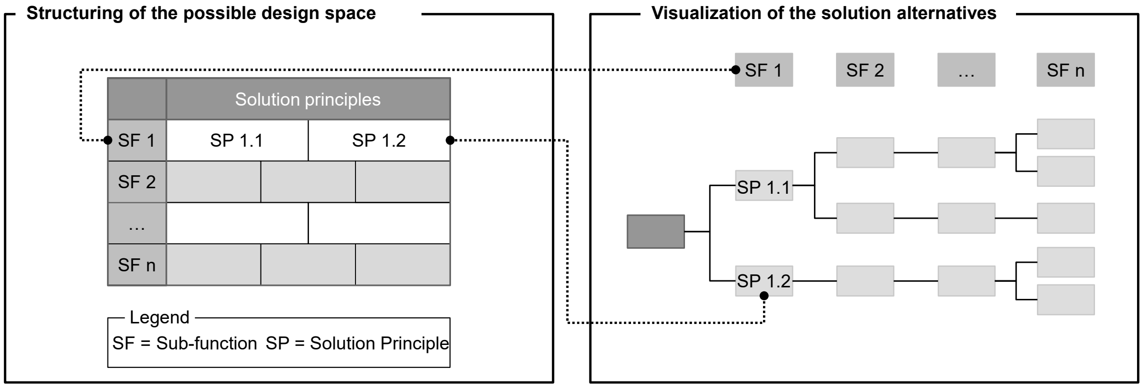

Figure 2. Visualization of the design solution alternatives by the aid of the alternative tree

Based on the identified product design solution alternatives and the possible solution principles the level of uncertainty of the solution principles has to be determined. Since the effects of the uncertainty of the information is dependent on the solution principles itself the evaluation of the level of uncertainty has to be performed on the level of the solution principle.

3.2 Evaluation of uncertainties of solution principles

In order to evaluate uncertainty of product design solution principles it is necessary to analyze the dimensions of uncertainty. Typical uncertainty dimensions are for example unsecure customer requirements, the performance of future competitors' products as well as the knowledge about the implemented technologies. Based on an intensive literature review with the focus on the description of the product development project, the development process as well as the design space the three dimensions market/customer requirements, product technology and production process have been further detailed. The performed review allowed the identification of the uncertainty factors influencing the three dimensions. The results of the uncertainty dimension and its main uncertainty factors are shown in Table 1.

Table 1. Main factors of the uncertainty dimensions

Market/Customer requirements	Product technology	Production process
▪ Knowledge of market ▪ Degree of requirement specification ▪ Availability of resources	▪ Product novelty ▪ Technology novelty ▪ Application experience of solution principle ▪ Degree of Complexity ▪ Knowledge about product structure ▪ Degree of variability	▪ Degree of process development ▪ Production process innovation ▪ Degree of production process requirements

For the evaluation of the uncertainty of a solution principle the effects of the uncertainty in each dimension on the solution principle has to be determined. Therefore, the uncertainty of a solution principle is calculated as the weighted sum of the uncertainty evaluation of each influencing uncertainty dimension:

$$SU_j = g_{pt} * UPT_j^{norm} + g_{pp} * UPP_j^{norm} + g_{CR} * UCR_j^{norm} \quad (1)$$

- SU_j: Uncertainty of solution principle j
- UPT_j^{norm}: standardized uncertainty value in the dimension product technology for solution principle j
- UPP_j^{norm}: standardized uncertainty value in the dimension product process for solution principle j
- UCR_j^{norm}: standardized uncertainty value in the dimension customer requirements for solution principle j
- $g_{pt,pp,cr}$: Weighting factor of the uncertainty dimensions

Thus for the determination of uncertainty of a solution principle the uncertainty in each dimension has to be evaluated. Therefore, the probability of occurrence and the resulting impact of the uncertainty factor related to the solution principle have to be taken into account. The uncertainty in each dimension, shown for the dimension product technology, is calculated as follows:

$$UPT_j^{norm} = \frac{\sum_{y=0}^{z} P(PT_y(j)) * I(PT_y(j))}{UPT_{\max}} \quad (2)$$

- UPT_j^{norm} : standardized uncertainty value in the dimension product technology for solution principle j
- $P(PT_y(j))$: Probability of occurrence uncertainty factor y for solution principle j
- $I(PT_y(j))$: Impact of uncertainty factor y for solution principle j
- UPT_{max}: maximal uncertainty value in the dimension product technology

As one of the main problems for an assessment of uncertainty especially in early product development phases is the availability of quantified data, the determination of the probability and the impact of the uncertainty factors have to be carried through a qualitative assessment with internal and external experts. Therefore, for the estimation of the probability of occurrence and the impact on the solution four different levels (high, average, low, not relevant) have been developed (Table 2):

Table 2. Evaluation of probability and occurrence

Rating (verbal)	Rating (numeric)
No probability/impact:	0
Low probability/impact	1
Average probability/impact	3
High probability/impact	9

Based on this evaluation the uncertainty of the existing solution principle can be derived and due to the aggregation of the uncertainty dimensions visualized in the shell model of uncertainty. Therefore, the shell model is divided into functional areas to compare the uncertainty level of alternative solution principles. For the classification of the uncertainty level an equal distribution of the concentric circles is assumed. Thus an uncertainty evaluation of less than 0.33 leads to a classification at the inner Layer of the shell model (see Figure 3).

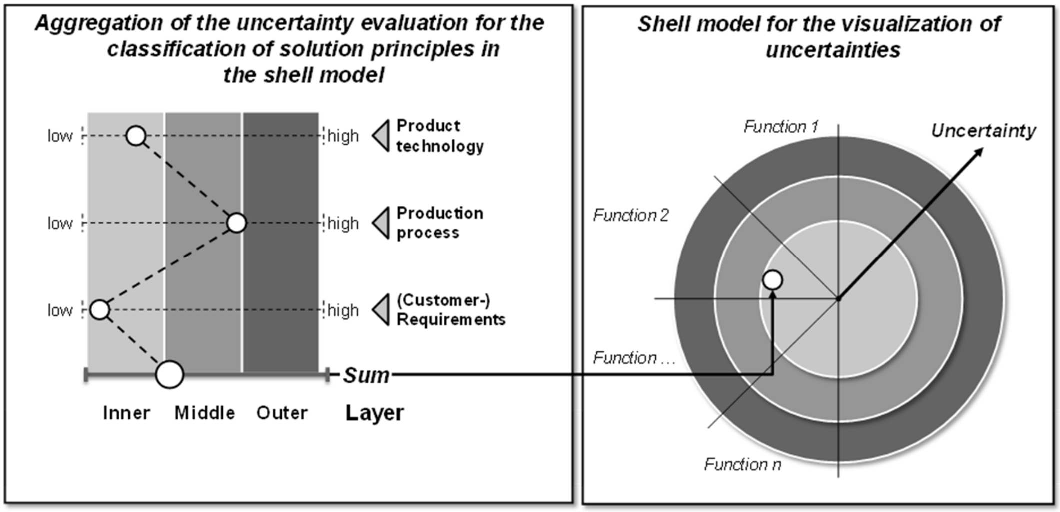

Figure 3. Evaluation of uncertainty of product solution principles

The evaluation and visualization of the uncertainty identifies these solution principles, which are more uncertain and which are more robust with regard to the present information. However, a final decision about the parallel development of different solution principles cannot be determined on the basis of the uncertainty level. In addition, the interactions and interdependencies of the solution principles in the context of the design space have to be analyzed in order to derive the further developed product design solution alternatives.

3.3 Derivation of design sets

The analysis of the uncertainty of solution principles focusses on the determination of the implications of the level of information on the selection of a solution principle and thus can be described as an internal perspective. Since this internal perspective is not sufficient enough to decide whether a parallel development is necessary or not an analysis of the level of interaction of a solution principle, as an external perspective, within the design space has to be performed. Both, the internal and external perspective have to be combined to an integrated design model to derive the parallel development of solution principles. The aim of the integrated design model is to derive generic design strategies for the parallel development of solution principles for each product function. Thus the model is not aiming to determine a fixed size of the design space or the exact number of the parallel developed solution principles.

Due to the good comprehensibility and interpretability the portfolio analysis is used as a basis for the derivation of generic strategies of the integrated design model. Therefore, the level of interactions as external perspective and the uncertainty analysis as an internal perspective are combined to the convergence-uncertainty-portfolio (see Figure 4).

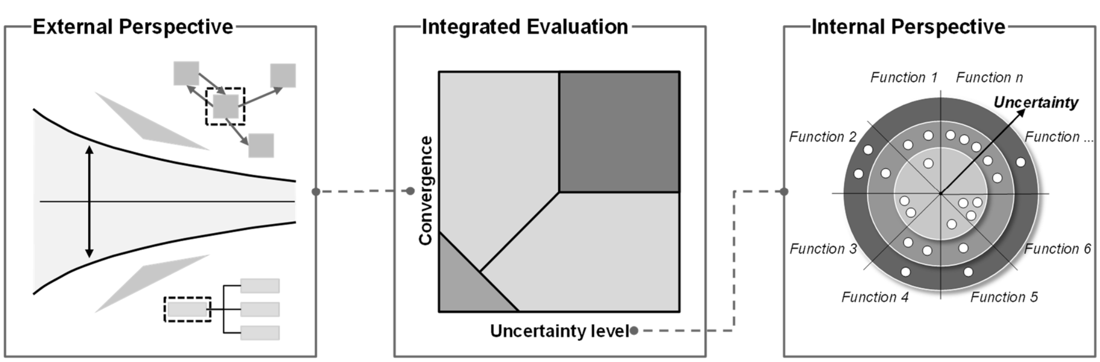

Figure 4. Integrated evaluation with the convergence-uncertainty-portfolio

In order to build the convergence-uncertainty-portfolio the degree of convergence has to be defined. The degree of convergence serves as illustration of the interactions of the functions in the subsystem and the interactions of the solution principle in the design space. Therefore, the standardized degree of functional interaction of solution principle as well as the degree of reduction of design solution alternatives by focusing on a solution principle has to be determined. Thus, the degree of convergence describes the external influence of the subsystem on the principle solution in the design space and is calculated as follows:

$$CD_j = ID_j^{norm} * RSA_j \tag{3}$$

- CD_j: Degree of convergence of solution principle j
- ID_j^{norm}: standardized degree of functional interaction of solution principle j
- RSA_j: Degree of reduction of design solution alternatives by focusing on solution principle j

The degree of functional interaction reflects the level of interaction of a function within the product structure and thus considers that the influence on a solution principle and from a solution principle to the other solution principles affects the parallel development within a function. The standardization of the degree of interaction is evaluated by weighting the degree of interaction of the function relative to the maximum degree of interaction within the subsystem and is calculated as follows:

$$ID_j^{norm} = \frac{IDj}{ID_{\max}} \tag{4}$$

- ID_j: Degree of functional interaction of solution principle j
- ID_{max} maximum value of functional interaction within the product structure

Therefore, the degree of interaction of the individual functions is evaluated for the functions initially. The degree of interaction represents the ratio of the passive to the active sum of the interdependency network of the functions. Since, at least in theory, both the passive and the active sum can be "0" the value range is change by the addition of "1" to the range [1, ∞). Thus, the degree of interaction of a function f is calculated as follows:

$$ID_j = \left[\frac{1+PS_f}{1+AS_f}\right] \tag{5}$$

- AS_f: active sum of function f of solution principle j
- PS_f: passive sum of function f of solution principle j

Since the standardized degree of interaction reflects the interactions within the subsystem on the functional level, also the interaction of a solution principle in the design space has to be determined. The interaction of a solution principle in the design space is calculated by evaluating the degree of reduction of design solution alternatives within the design space by focusing on a solution principle.
The reduction of design solution alternatives describes the relative proportion of design solution alternatives within the design space, which are using the considered solution principle. With regard to the systematic control of the design space the degree of the reduction of design solution alternatives is used to describe the influence of a solution principle on the size of the design space. An increasing value of the degree of reduction of design solution alternatives means a higher flexibility for the selection of the solution principles in other functions. Accordingly, the degree of reduction of design solution alternatives (RSA) is calculated as follows:

$$RSA_j = \frac{SA_{max} - SA\#_j}{SA_{max}} \quad (6)$$

- SA_{max} maximum value of design solution alternatives within design space
- $SA\#_j$: number of design solution alternatives including solution principle j

Accordingly, the two dimensions, the degree of convergence and the level of uncertainty are building the convergence-uncertainty-portfolio, which is used for the derivation of the generic design space strategies. Therefore, the degree of convergence is plotted on the ordinate and the level of uncertainty on the abscissa of the portfolio. Both dimensions have a value range of [0, 1]. Due to the differentiation between a high and low degree of convergence as well as between a high and low uncertainty level the portfolio can be divided into four areas. These four areas are used to determine the generic design space strategies for the parallel development of solution principles for each product function. Thus, the four design space strategies are as follows:

- Strong alternative oriented parallel development
- Convergence oriented parallel development
- Uncertainty oriented parallel development
- Focused solution principle development

The design space strategy "strong alternative oriented parallel development" of a function is aimed at safeguarding the solution principles both in terms of existing uncertainty and the degree of convergence of the existing design solution alternatives in the design space. Within the portfolio, this design strategy is located in the upper right corner. The focused solution development principle corresponds to the counterpart of the strong alternative oriented parallel development. The strategy "focused solution principle development" is equal to a selection of the preferred solution principle. Due to the low level of uncertainty and at the same time low degree of convergence a safeguarding of the preferred solution principle is not necessary. In the portfolio the generic strategy is locates in the lower left area. Notwithstanding of the typical division of a portfolio in four equal quadrants, the strategy field forms a triangle. The classification of the shell model of uncertainty is used for the determination of the boundaries of this area. The design strategy "convergence oriented parallel development" aims at securing the solution principles due to the high degree of convergence. A high degree of convergence restricts the flexibility for a parallel development of solution principles for other product functions. The "uncertainty oriented parallel development" also corresponds to a factor-based parallel development and aims at safeguarding the uncertainty of the solution principles due to the parallel development. The safeguarding within this design space strategy is performed with regard to the identified uncertainty dimensions. Thus, the design strategies helps avoiding iterations in the development process (see Figure 5).

Based on the defined generic design space strategies the derivation of the valid strategy for each function has to be determined. Therefore, the solution principles for each function have to be prioritized with regard to product cost and fulfillment of customer requirements. Due to the prioritization the preferred solution principles for a product function the valid design space strategy for the function is determined by the position of the preferred solution principle in the convergence-uncertainty-portfolio. Accordingly to the position in the portfolio either the preferred solution principle is combined with regard to the uncertainty (strong alternative oriented parallel development, uncertainty oriented parallel development) or combined with regard to the reduction of the design solution alternatives (strong alternative oriented parallel development, convergence oriented parallel development).

Due to the determination of the design space strategy for each function of the product the solution principles are determined, which are developing in parallel. Thus, the developed method leads to a systematic reduction of alternative solutions by a transparent evaluation and selection of the solution principles.

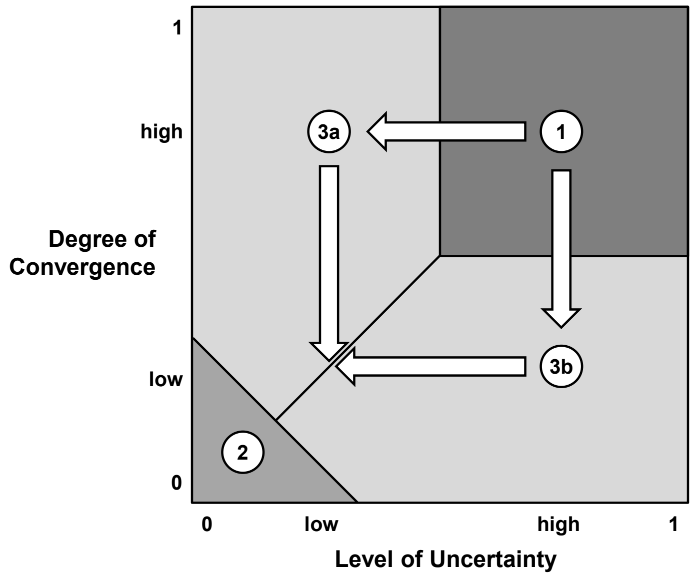

Figure 5. The convergence-uncertainty-portfolio for the systematic combination of solution principles

4. Conclusion

Previous research in the field von set-based design has focused either on the evaluation of the design space without analyzing the included design solution alternatives in detail or on a detailed description of construction parameters for one single component. This paper analyzes the design space from the perspective of the different solution principles in the conceptual phase of the development process and confirms the interdependency of design solution alternatives within an efficient and effective product development. Therefore, based on the research activities and expert interviews the designed method firstly evaluates the level of uncertainty of the solution principles and the degree of convergence. Both perspectives are combined to an integrated design model for the determination of the parallel development of solution alternatives based on generic design space strategies.

Future research will concentrate on the refinement of the presented approach and a further validation within an industrial development project.

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