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A PROCESS MODEL FOR DESIGNING FUZZY PRODUCT STRUCTURES

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1. Introduction

The strategy of mass customization is a current approach in industrial production, based on e.g. steadily growing pressure of competition, partly saturation of conventional markets, and increasing globalization. Nowadays, customers can easily achieve information on competing products, their quality and prices, and they are no longer limited to local product offers. The approach of mass customization tries to satisfy each customer with his individual designed product and integrates customers in the design process. Furthermore, mass customization claims to roughly keep up with mass produced products in product quality, prices, and delivery time. To meet these demands, it is necessary to adapt conventional product structures, as they do not allow an adequate representation of flexibility.

Typically used product models mostly generate stiff structures and offer variant elements to the customers to choose from. Such product models, with often many hundreds of optional elements, lead to large quantities of theoretically available products, which require intensive management efforts. Due to their mutual influences and constraints, extremely complex networks of interdependencies arise between the variant elements. However, this does not represent real product individualization, because each possible variant specification has to be explicitly pre-designed by the manufacturer. If based on such product models not so far anticipated customer demands have to be realised, large parts of the design process will be newly run through (with negative effects on delivery time and costs). Starting from the specific part design the product designer also has to assure the integration in the entire product as well as the safety tests.

The objective of the here presented work is a methodical support for designing flexible product structures to simplify the specification of explicit products. If such product structures (named product spectra) have been set up, an easier deriving of individual products according to predetermined customer demands gets possible.

2. From variant modelling to a comprehensive product spectrum

The need for variants of parts and products has led to a general change in generating product structures in the design process. Strictly hierarchical interrelations are designed to represent the structure of non-variant components and assemblies. The integration of a possible variability into such simple and stiff structures brought intensive cross-linking as well as the application of a widely enlarged semantic description of interdependencies. Standard component structures only possess (possibly directed) dependencies between two elements at each time; all interdependencies in such a network are independent from each other. The integration of variants and optional elements induced the demand for an adoption of the Boolean logic and enlarged product structures to direct influences between interdependencies. With these new possibilities, the depiction of extremely complex conditions gets possible. However, the integration of new elements to the structure or the adaptation of existing ones is distinctly more difficult and extensive. Even if already a large number of variants exist in a predetermined product structure, the efforts for integration new ones will not decline. Furthermore, the offering of variants or options by the manufacturer will never lead to a real individuality for customers. Variants are always pre-designed specifications the customer can choose from. If based on such product structures individual customer demands have to be realized, there is no difference to a pre-designed variant for the manufacturer. Thus, the large efforts of development and integration rest still the same.

A possible approach, including the partly pre-planning of product structures, is the systematic creation of product spectra. This leads to a noticeable reduction of complexity when specific products with individualized elements has to be build up. For this pre-planning interdependencies between incompletely specified product elements have to be created and analyzed in advance. Thus, a product spectrum mainly consists of unspecific elements and degrees of freedom, which have to be concretized with explicit characteristics and values to obtain a physical product. Therefore, a comparison between a product spectrum and a basic product (from which variants will derive from) is not possible. Beginning with an abstract model of a product spectrum, a single product has to be specified by interaction with the spectrum and consideration of possibly only implicitly predetermined limits [Pulm 2003].

3. Process of product spectrum interaction

Mostly the designer possesses the possibility to access an exemplary product or a collection of elements (derived e.g. from a list of requirements) for generating a first version of a product spectrum. In either initial case, the elements are not available in an appropriate structure and are entered in an adjacency matrix in an unsorted manner. This applied matrix corresponds to the definition of the Design Structure Matrix – DSM [Browning 2001], where identical elements are listed in the same order at both axes (e.g. equal element in first row and first column). In the here presented approach the so called component-based DSM is adopted, which describes interdependencies between elements by spatial, energy, information or material linking. Depending on the product and problem field in question one specific type of interdependency is chosen for further processing. After this, the existing interdependencies are entered in the matrix in accordance with the rule “column element affects row element”. A collection of basic interdependencies between considered elements, which is accessible by approved algorithms, can be noticed as result of this first process step.

In the further proceeding the elements of the adjacency matrix are to be sorted in three groups by their affiliation to “basic elements”, “variant elements” and “optional elements”. Basic elements are defined as elements of general and essential existence in the product. They are integral part of the basic structure of the entire product spectrum. Furthermore, basic elements point out the limits of possible product customization, as their general existence in every product (derived from the product spectrum) is part of the product definition itself. For example, the lead could be defined as a basic element of a pencil. Thus, there are no possibilities of individualization concerning the existence of a lead in a customized pencil. Without a lead the product would not be a pencil any more (and could not be depicted by the pencil product spectrum).

A clear distinction between “variant elements” and “optional elements” cannot be easily indicated, as the possibility of an optional element choice (existence or absence) can go along with variability in attributes of the same elements (e.g. existence and specific colour). In this case, it must be considered, which one of the two criteria (variability or option) prevails. In the here presented approach we propose an easy evaluation by distinct values [Bernard 1999] as decision support. Both, variability and option of an element are rated by the values 1, 3, or 9, corresponding to strong, medium, or low variability or option. A consistent method to assign an element in question to one of the specific element types is to build the quotient of both values (variability/option). Resulting values around 1 refer to “variable elements”, whereas very small or big values refer to a preponderating optional element type. The result of the classification by element types is a cluster of partial matrices (see Figure 2). Mutual interdependencies in-between elements of the same element type, as well as between different element types can be easier interpreted and approached according to requirements (e.g. discussing possible conflicts, which result from adding optional elements to the basic structure). In the following the interdependencies within the partial matrices are to be analyzed in detail. For this reason, algorithms and use of intensive computer support [Kusiak 1999] enlarge the conventional possibilities of the DSM. The intention of this process step is to discover and depict specific partial structures and exposed elements in the comprehensive network. Such partial structures can be hierarchical ordered sub-ranges, i.e. that adaptations to the upper elements in a hierarchy affect the entire subordinated structure. If elements belonging to such sub-ranges are adapted, they show particular impact on further elements. Examples for exposed elements are so called active components (with above average quantity of impact on other elements), bridge elements (providing the only interdependency between two partial graphs), and start and end nodes.

As long as the matrix in question does not exceed a certain size, procedures known from the conventional DSM methodology can be used to manually carry out the analysis [Pimmler 1994, Ulrich 2000]. An important advantage of manual analysis is that the designer is dealing intensely with the structure and so gets a better understanding of the performed steps. However, this sort of structural analysis is not only limited by matrix size (and clarity), but rather the mathematical complexity of the needed analysis procedures. Particularly the execution of non-monotone algorithms is required for the automated clustering (merging of elements to groups) [Backhaus 1996, Hartigan 1975]. This asks for extensive computational attempts and is out of question for a manual treatment.

After analyzing the interdependencies in-between of partial matrices, dealing only with one element type, the forth process step considers the cross-linking between different element types. Depending on the specific use case, two different procedures are applicable: if a product spectrum already exists and has to be analyzed, this process step allows the determination of variant and optional elements with critical influence on basic elements. The results of these analysis attempts can further lead to design adaptations of basic elements with the intention of minimizing or even avoiding critical influences to them. A direct consequence of these measures is a raising suitability for individualization demands.

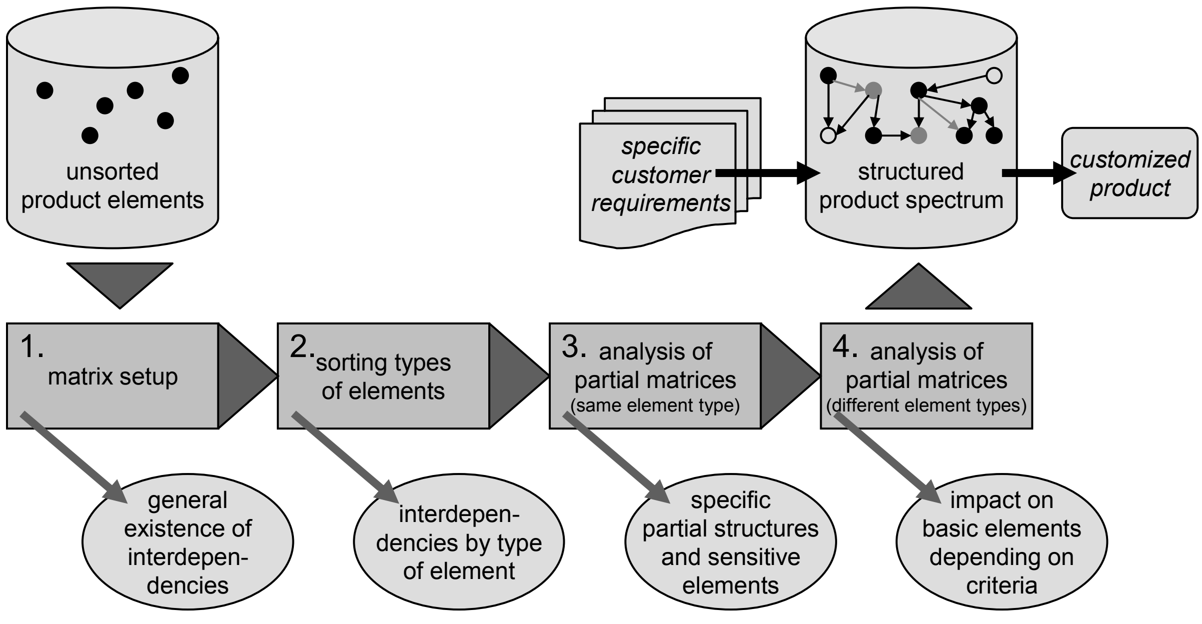

Figure 1. Process of product spectrum generation

In the second case, a primary basic product serves as starting point for generating the product spectrum. Now the execution of the forth process step helps to identify structural ranges, where measures of individualization are easily applicable or unsuitable (due to critical conflicts). Thus, it gets possible to offer the customer specific product ranges for a preferred customization, because of the knowledge of few critical interdependencies in these spectrum ranges.

Figure 1 depicts the process of product spectrum generation i with the four sequenced process steps. Further, the derived results of each step are mentioned. Because of its complexity and importance for the process, the analysis of partial matrices (steps 3 and 4) will be discussed in detail in the following.

4. Extended analysis of partitioned matrices

Figure 2 depicts the overview over basic correlations in sorted element matrices, as they are available after performing the second process step. The analysis of interdependencies between same element types (third process step) is executed in the partial matrices along the diagonal, named Ia, Ib, and Ic in Figure 2.

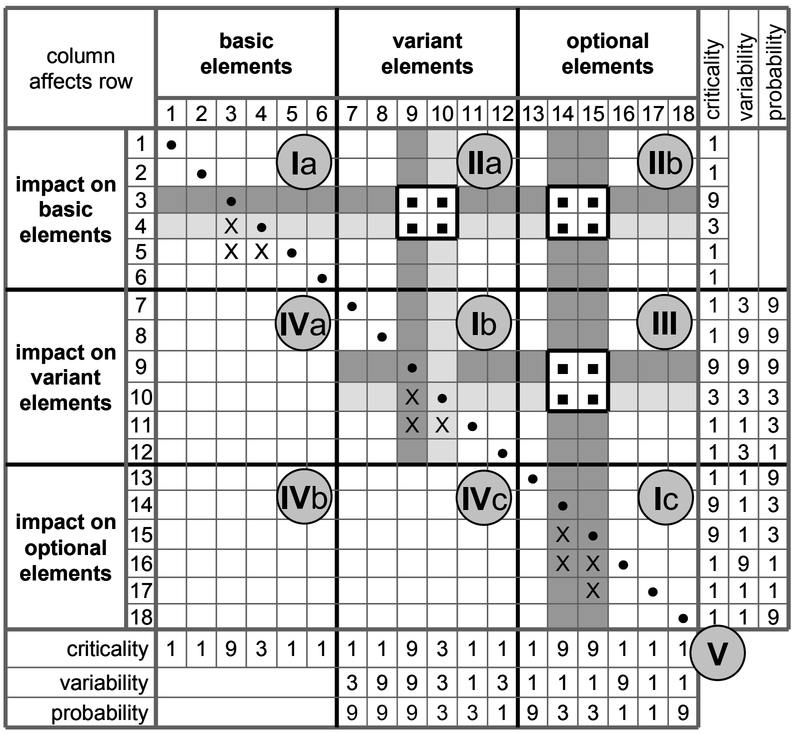

Figure 2. Overview of basic matrix layout for product spectrum interaction

If specific partial structures and exposed elements are determined, attention must especially be turned to the identification of critical structure attributes (named criticality in Figure 2). The same distinct values 1, 3, and 9 are applied for an evaluation concerning critical elements, as they were used for the variability and optional attribute. In Figure 2 the rows and columns of elements with high and medium critical values (here the criticality results from elements' position in hierarchical sub-structures) are shaded in grey (above the diagonal).

Now in the forth process step the interdependencies between elements of different element types are discussed. Analyses are executed in the partial matrices IIa, IIb, and III. The matrices IVa, IVb, and IVc (laterally reversed to the diagonal) are not further considered, as they represent the impact of basic elements on variant and optional elements (IVa, IVb) or from variant elements on optional elements (IVc). Due to the initially defined proceeding, the basic elements represent the primary product definition and additional elements have to be adapted to them – concerning the constraints given by these basic elements.

First intention of the matrix analyses IIa, IIb, and III are the determination of interdependencies, which are critical, due to the structural embedding of involved elements. Thus, the linking of two elements, both classified as critical elements (process step 3), is also constituted as critical. Such interdependencies are exemplarily depicted in Figure 2 (rectangle symbols). The element couples indicated as involved in critical interdependencies have to be examined in detail in the further design process.

Beside of critical interdependencies based on critical structures, the matrices IIa and IIb also have to be analyzed concerning critical degrees of variability and probability of existence. It is expedient to examine the impact of the dimension of variability on basic elements. The used parameters for describing the impact of variant elements (IIa) and optional elements (IIb) on basic elements are the intensity of impact and the probability of impact.

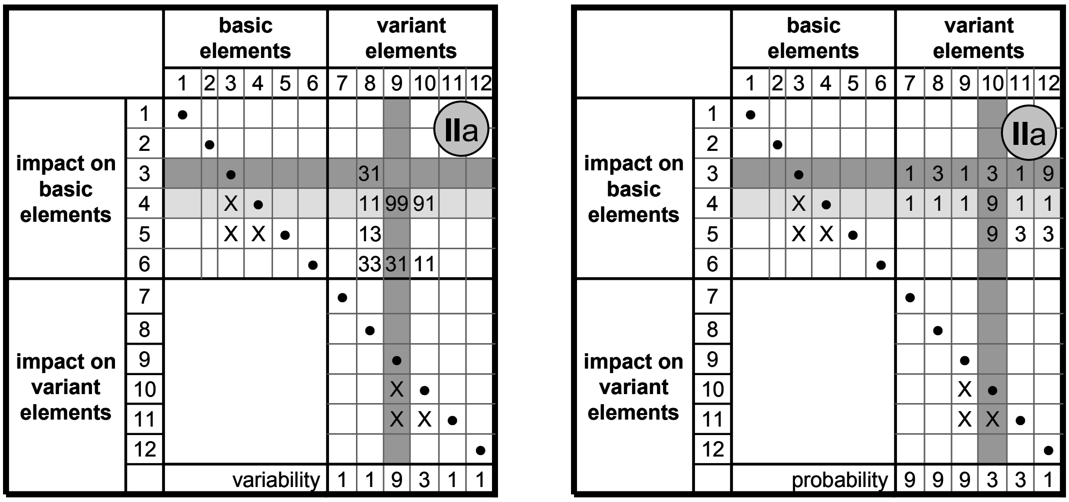

Figure 3. Influence on basic elements by variant elements

As it can be seen in Figure 3, analyses concerning interdependencies between variant elements with critical variability and critical basic elements (because of their structural embedding) are characterized by both parameters. The first number in the cells is the value for the intensity of impact, the second one the value for the probability. For analyses with the probability of variant elements as decisive criterion, the only needed interdependency parameter is the intensity of impact. The parameters are acquired by the already explained evaluation of three values 1, 3, and 9.

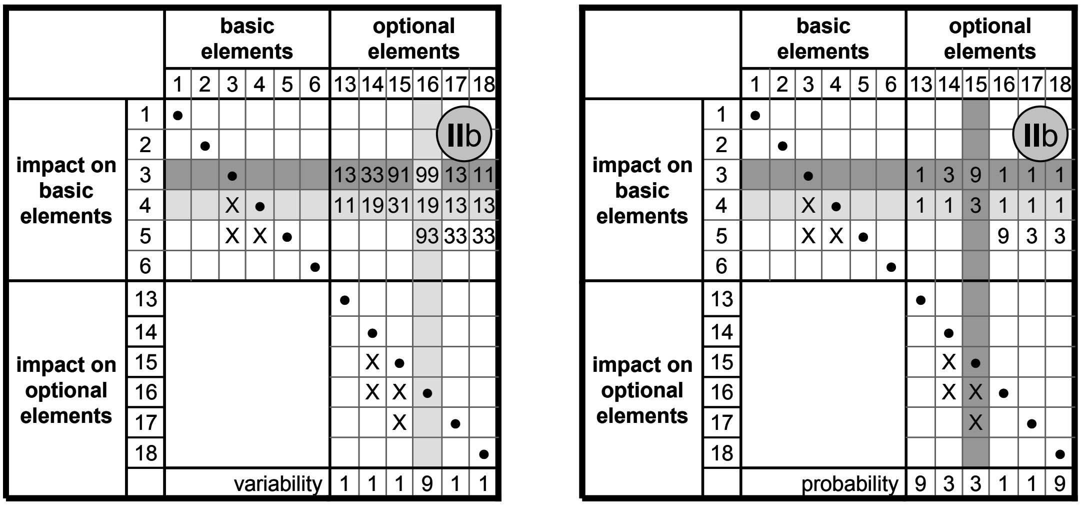

Figure 4. Influence on basic elements by optional elements

The left matrix of Figure 3 depicts the analysis of impact on basic elements by variant elements, concerning their degree of variability. Here element 9 possesses a high degree of variability (column shaded in grey). Due to their critical structural embedding, the basic elements 3 and 4 are considered for closer examination. As there is no dependency between element 9 and element 3, but the intensity of impact as well as the probability of impact from element 9 to element 4 is high, only this second interdependency must be treated in the further design process – with the intention to restrict the impact. If this is not practicable, also the variability of element 9 can be reduced to prevent a conflict. However, reducing the variability means decreasing possibilities of individualization for customers.

The right matrix in Figure 3 displays further analyses of impact on basic elements by variant elements. Here it concerns the degree of probability of variant elements' existence. Here element 9 possesses a high probability, but only low intensity of impact to the critical basic elements. Element 10 (with medium degree of probability) possesses a high impact on basic element 4 – thus, it is relevant for further design optimization of the product spectrum.

Figure 4 shows the exemplary analysis of the fourth process step in the partial matrix IIb. To evaluate the impact on basic elements by optional elements the same proceeding is used as explained before. In the example of Figure 4 the interdependencies between element 16 and 3 (respectively 4) in the left matrix and element 15 and 3 in the right matrix can be identified for further design activities.
Actually, we applied the presented process model to an high-pressure washer. Here the entire matrix consists of 78 elements. The specific information in the partial matrices facilitates the access to relevant element groups. Thus, with relatively little evaluation effort, the overall impact of enlarging existing product variability could be pre-estimated and some limiting basic elements were identified. However, the acquisition of evaluation values as well as the identification of important interdependencies apparently requires further computational support, especially when the product model will be more detailed in further considerations.

5. Conclusions and further work

The presented work permits the structured planning of product spectra as a base for easier planning of product customization. By applying the matrix-oriented analysis method to networks of interdependencies, the designer is supported in finding interdependencies and element constellations with a high probability of conflicts between optional, variant, and basic elements. The proceeding of analysing is derived from established methods of product structure planning. But due to enlargement by adopted parameters and evaluation values the intensive use of computer support is indispensable. Beside of complex algorithms, also the visualization of specific constellations and exposed elements inside of a comprehensive network is an important domain for software support in the future.
The presented approach was so far examined by interactions in relatively small product constellations; for a further detailing and optimizing of single process steps as well as the entire approach an evaluation with more complex products is to be done.

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