

ELEMENTARY DESIGN METHODS AND THEIR BENEFITS FOR RESEARCH AND PRACTICE

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ABSTRACT

This contribution presents an approach to defining elementary design methods, which differs substantially from previous ones. It grew out of the feeling of unease concerning the status of design methodology. As much as the number and variety of publications of “newly invented” design methods increases as much the attractiveness for designers working in industry seems to decrease. It was the desire, “to tidy up” this obscure body of prescriptive procedures for design work which motivated to start a kind of consolidation project. The key concept to overcome the problems was the analogy to the system of chemical elements, which reduces the incredible huge amount of materials and substances to about one hundred chemical elements. If one succeeds to adapt this approach to the body of design methods, fascinating perspectives arise for a convincing structuring of design methods, for improved performance in teaching and learning and for a huge degree of freedom in terms of flexibility in application.

Keywords: Design Methods, Elementary Methods, Syntax, Semantic, Method Structure

1 INTRODUCTION

Design research offers a huge amount of design methods to improve efficiency and effectiveness of design work. However, in fact, a major amount of them does not leave the hemisphere of academia. Most design methods do not have a long-term impact nor in education either in practice [1]. In addition, a substantial amount of methods seems to be only derivations or aggregations of previous published ones. In total, the world of design methods for a potential user in design practice appears rather heterogeneous and even obscure.

Further, the application of design methods is rarely supported by advices how to adapt them to a specific design situation. Obviously, no fully carried out QFD e.g. with its four “Houses” is needed in each design task. To concentrate on only one house, in order to reduce this to the core support of a specific design task and to leave useless parts demands substantial competencies of a user. These demands could not be expected at all from the majority of design practitioners. The inflexibility and even rigidity of design methods are major obstacles hindering a widespread application in industry.

Triggered by the vision of a limited set of elementary design methods representing basic prescriptive procedures, a corresponding research program was initiated at TU-Darmstadt. The objectives were to extract method-inherent basic procedures by analysing current design methods to evaluate these so-called *elementary design methods* by re-assembling them to known design methods and to create specific sequences of elementary methods according to a specific task and design situation.

In total, the approach aims to tidy up the world of design methods [2], which seemed to be a most demanding, even utopian goal regarding previous attempts of various authors. This contribution presents the way of analysing and reasoning as well as the results of the project, most of them the PhD-thesis of Walter [3] describes in detail.

2 STATE OF THE ART

A wide range of research work intends to capture the basic nature of design methods or to improve application by giving advices. Some approaches structure design methods according to specific characteristics like generalised steps of problem solving [4] or specific objectives [5]. Some approaches like the Process oriented Method Model (PoMM) [6] or the Basic Structure of Design Methods from Dobberkau [7] focuses on how to describe the variety of methods more generally to see similarities

and differences. More often one can read approaches linking methods to design phases [8, 9], or typical applications [10]. Several attempts [11, 12] in the past define elementary design methods as basic prescriptive procedures. Doing so, researchers wished to reduce the huge amount of published design methods to a limited set of basic (elementary) methods that represent the “petri dish” of design methodology.

Nevertheless, there is no consensus within the community about the preference of a specific approach. It seems to be a remarkable gap between the challenging demands of the individual researcher creating his own structure of design methodology and the perceptible benefits of these approaches for the research community. Beyond it, the use of such approaches for improved transfer into design practice and for long-lasting application seems to be quite doubtful.

3 METHODOLOGICAL APPROACH

This contribution presents an approach to define elementary design methods, which differs substantially from previous ones. Its origin goes back to an as obvious as convincing perception while looking at the style of the presentation of most design methods.

3.1 Basic recognitions

Regarding a presentation of the second House of Quality (HoQ) of a Quality Function Deployment (QfD) one can see easily, its vector and matrix based structure (figure 1).

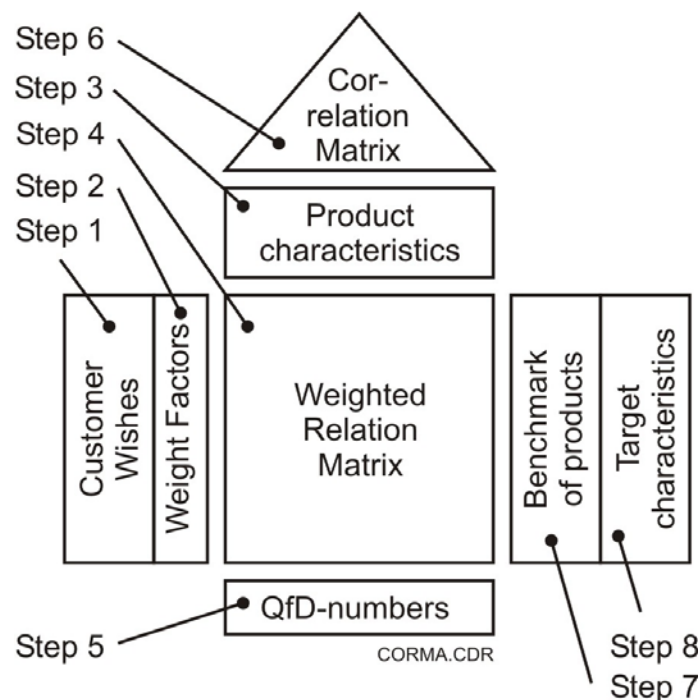


Fig. 1: Second House of Quality (HoQ) of Quality function Deployment (QfD)

Same as other methods like Morphological Box, Requirements List, Evaluation Charts or Design Structure Matrix the HoQ links vectors or matrices either to themselves or to other vectors resulting in new vectors or matrices. Beginning at the left side of the HoQ a user has to follow the procedure:

1. List customer wishes in the first column (vector of customer wishes)
2. Link them to a vector of weights (vector of weights)
3. List product characteristics
4. Link the customer wishes to product characteristics (central matrix)
5. Connect weight of customer wishes with product characteristics to a vector of QfD-numbers
6. Link product characteristics to themselves (correlation matrix or roof of HoQ)
7. Connect customer wishes to product properties
8. Connect product characteristics to target characteristics

In fact, the QfD may be reduced to a sequence of operations with vectors and matrices.

3.2 The substantiality of the linking-approach

The PhD-thesis of Walter [3] enlarged this basic assumption and proved it by analysing a remarkable variety of design related methods. Almost 90 different methods in the field of systematic design, quality management, creativity techniques and machine elements were analysed in regard to verify or falsify the vector-matrix approach. The detailed analysis results surprisingly in the fact, that besides all differences in objectives, content, application area or presentation style in principle one may depict all related design methods in the vector-matrix approach (table 1).

Table 1: Examples of a stepwise vector-matrix generation and transformation in some design methods

Morphological Box	Requirements List	Failure Mode and Effects Analysis (FMEA)	Calculation of life-time of roller bearing
List functions	List characteristics of requirements	List objects (components or parts of a product)	List forces (axial, radial)
List solutions for a specific function	Link values to these characteristics	Link potential failures to objects	Connect forces (to loads P)
Link solutions to functions	Link type of requirement to requirements	Link potential effects to failures	List geometric properties of the bearing
	Link responsible party to requirements	Link potential reasons to failures	Assign dynamic properties of the bearing (C-factor)
		Connect potential reasons with values (to probability of occurrence)	Connect dynamic properties with loads (to C/P-factor)
		Connect potential failures with values (to probability of detecting)	Assign exponent p for the specific case of bearing (to C/Pp)
		Connect potential effects with values (to importance for customers)	Connect C/Pp with revolutions per hour to lifetime
		Connect three probabilities (to risk priority code))	
		Assign measures to the risk priority code	

Even if different researchers were asked to transform design methods into the vector-matrix style, they succeeded to do so without serious trouble and the results were identical or at least similar.

Reasoning these results at that status of the research work, it was assumed, that these findings are not only a manifestation of a formal aspect of presentation, but indicates a basic content concept behind the approach and maybe provides the key for a better understanding of the nature of methodical work. Perhaps designers and engineers use vector- and matrix-based presentations not only out of habit, but because they represent best cognitive processes in engineering thinking especially for reducing complexity of “real world problems”.

3.3 The list approach

3.3.1 Elements and relations

Based on the concept of the modularization of contents, the research project “the key to innovation” [13] realises first, the vector-matrix approach was analysed in detail. In this project later performed in the *pinngate* project [6], design methods may be divided into syntactic and semantic units. Syntactic units are strings or characters without an explicit meaning, whereas semantic units represent contents with an explicit meaning. Analysing nearly 90 design methods 2 types of syntactic units, the elements and the relations became obvious.

Elements are items, which are processed and/or regarded in design methods. Typical elements, which occur repeatedly in design methods, are:

- Processes
- Functions
- (Physical) Effects
- (Working) Principles
- (Real) Objects (like parts, components, units)
- Properties

- Characteristics and
- Values.

Of course, other types of elements may occur in specific design methods, but the eight named above represent a vast majority of elements currently used. Processes, functions, effects, principles and objects represent specific product models [14] or products whereas properties, characteristics and values describe them according to the theory of technical systems [15].

Elements of the same type form an element vector, e.g. the vector of mechanical gears or the vector of values for indicating the probability of occurrence of a failure within the FMEA-method. Sometimes a vector of elements may degenerate to a single scalar. In this context, element vectors are called *lists*, which term creates the title of the approach called *list-approach*.

Relations, such as “is a”, are items which link different elements together. The analysis of almost 90 design methods results in a set of five basic relations mostly used:

- Is part of
- Belongs to
- May be separated in
- Is element of
- Is connected to

Elements and relations by themselves represent only syntax and have no - or rather no intended - semantic. The solution “cam drive” on its own is as meaningless concerning its content as the property “efficiency” or the relation “is part of”.

3.3.2 Operations

Semantic units are created when two list of elements are linked together by relations. A semantic unit is, e.g., “a cam drive has an efficiency” or “the efficiency has a value of 92%”. Applying a relation to a list of elements, we call it an *operation*. Concerning the fact that the five relations mentioned above cover most of the analysed design methods, one may argue, that these relations form a set of five basic operations:

- “*List*” is a special operation listing a set of elements in a sequential order (column or line). In fact, it is a kind of assigning, as these elements have to be taken from somewhere (catalogues, experience, textbooks...) and/or are assigned to a numbered sequence. However, due to its importance and frequency of occurrence the list-operation should be treated here as an own basic operation.
- “*Assign*” links two lists of elements belonging together. Concerning its semantic, it is “more” than the operation *list*, as the elements are not only listed but also put into a specific relation.
- “*Divide*” separates generic elements into sub-elements, which means, that the number of elements in the subdivided list is larger than the number of the generic elements.
- “*Merge*” may be seen as a kind of abstraction, which aggregates at least two sub-elements into a generic one. Therefore, this operation reduces the number of elements in the merged list.
- “*Connect*” is the most complex operation because it addresses hereby all types of functions between two elements. The operation especially covers logical, mathematical or heuristical relations between elements and results in a transformation of the original elements creating new information

The results of the operations assign, divide and merge are vector-oriented or matrices-oriented structures, the result of the operation connect is a value-imposed matrix. Figure 2 demonstrates the five types of operations by specific examples.

List
„is part of“

Function list
Sub-function 1: channelling material
Sub-function 2: channelling energy
Sub-function 3: channelling signals
Sub-function 4: connecting signal, material & energy
Sub-function 5: channelling energy
Sub-function 6: changing energy
Sub-function 7: channelling energy

Example: List of functions for a mixer

Assign
„belongs to“

Attribute	Data	Responsible
Cargo volume	350 L	Bg
Tank volume	60 L	Wt
Wheelbase	2,60 m	Wt
Breadth	1,85 m	Su
Length	4,92 m	Bg
Height	1,35 m	Wt
Seats	4	Su

Example: Requirement list for a car

Divide
„may be separated in“

Classification		Mainpart	Sharing part
Formclosed (positive)	indirect	profiled shaft	high torque transferable
	direct	Connection components	small torque transferable
Frictional grip	indirect	forcefit	small to big
	direct	clamping piece	medium torque transferable

Example: Structure of shaft-hub-connections

Merge
„is element of“

Vehicles			
Helicopter	with engine	aircraft	vehicle
Airplane			
Paraglider	without engine		
Tankship	cargo ship	ship	
Containership			
Ferry	ship for persons		
Cruise ship			
Tank	military	vehicle	
Limousine	cars		
Pick up			

Example: Design catalogue for means of transport

Connect
„is connected to“

more important (2) equal (1) less important (0)	than	A	B	C
A		1	2	0
B		0	1	2
C		2	0	1

Example: Weight factors for systematic evaluation

Figure 2: The basic operations within design methods

The limitation on five basic operations results from the limited number of relations mentioned before and represents no final border.

3.3.3 Elementary methods

It is now the linking of two elements with operations, which results in an *elementary method*. Typical elementary methods are “weighting of evaluation criteria”, “comparing solutions with each other” or “linking solutions to functions”. An elementary method therefore is a basic semantic unit with a meaning at its own. It represents new information for the user not known before. Elementary methods link two lists of elements with relation(s) and result in a scalar, vector or matrix (figure 3 left).

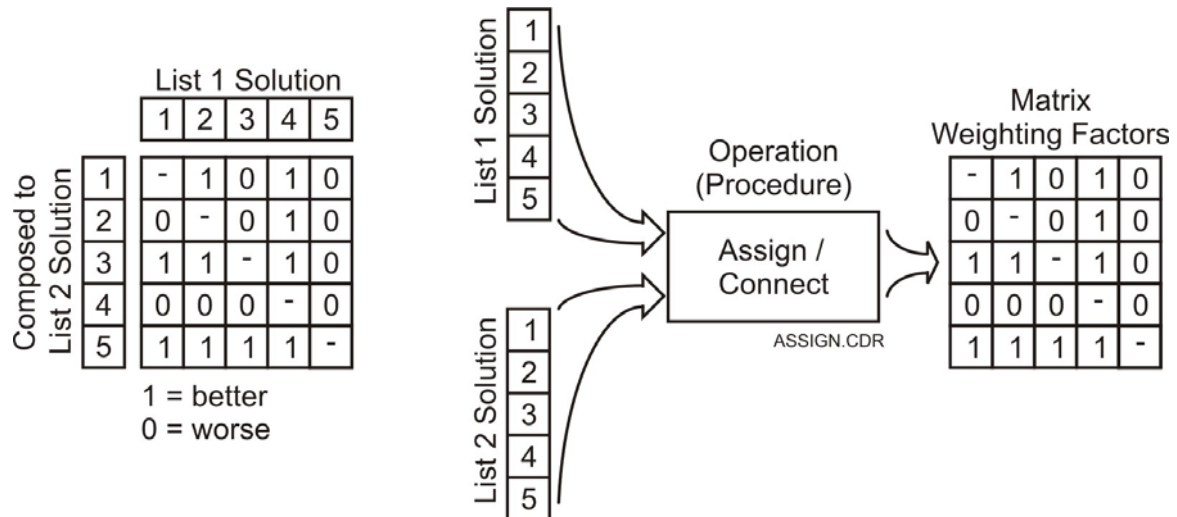


Fig. 3: The definition of elementary methods based on the list approach (left) and in the presentation style of the “Process oriented Method Model” (right) shown at the example of a paired comparison

Coming back to the approach of the *Process oriented Method Model (PoMM)* the list approach confirms it definitely. Both lists of solutions in figure 3 form the input, the operations “Assign” and “Connect” represent the procedures in PoMM and the output is the matrix of weighting factors. Altogether, the number of elementary design methods is based on just seven elements and five relations. The list approach now shows the beginnings of a precise definition and an almost complete set of elementary design methods.

4 EVALUATION

Based on the definitions of the list approach and the modularisation approach of the “*thekey to innovation*” project, current design methods now appear as containers [13], structured by a sequence of different elementary methods representing their “functional genomes”. Based on this concept about 40 design methods were traced back to a sequence of elementary methods. Figure 4 demonstrates a QfD of a mechatronic sensor in detail and figure 5 its functional genome.

Detailed investigations have shown that also graphically oriented design methods, like “functional decomposition” or calculation methods like “calculation of the lifetime of a shaft under external loads” according to DIN 743 [16], represent a multiple transformation process from a given input into the desired output according to the list approach. The only prerequisite to structure a design method into elementary methods is the one, that this method may be described in a presentation with scalars, vectors and matrices and related operations.

It is already obvious at this time, that structuring design methods on a well defined basis and with a simple applicable procedure may increase the understanding of the working principles of this method substantially and create a huge scope for development in terms of flexibility.

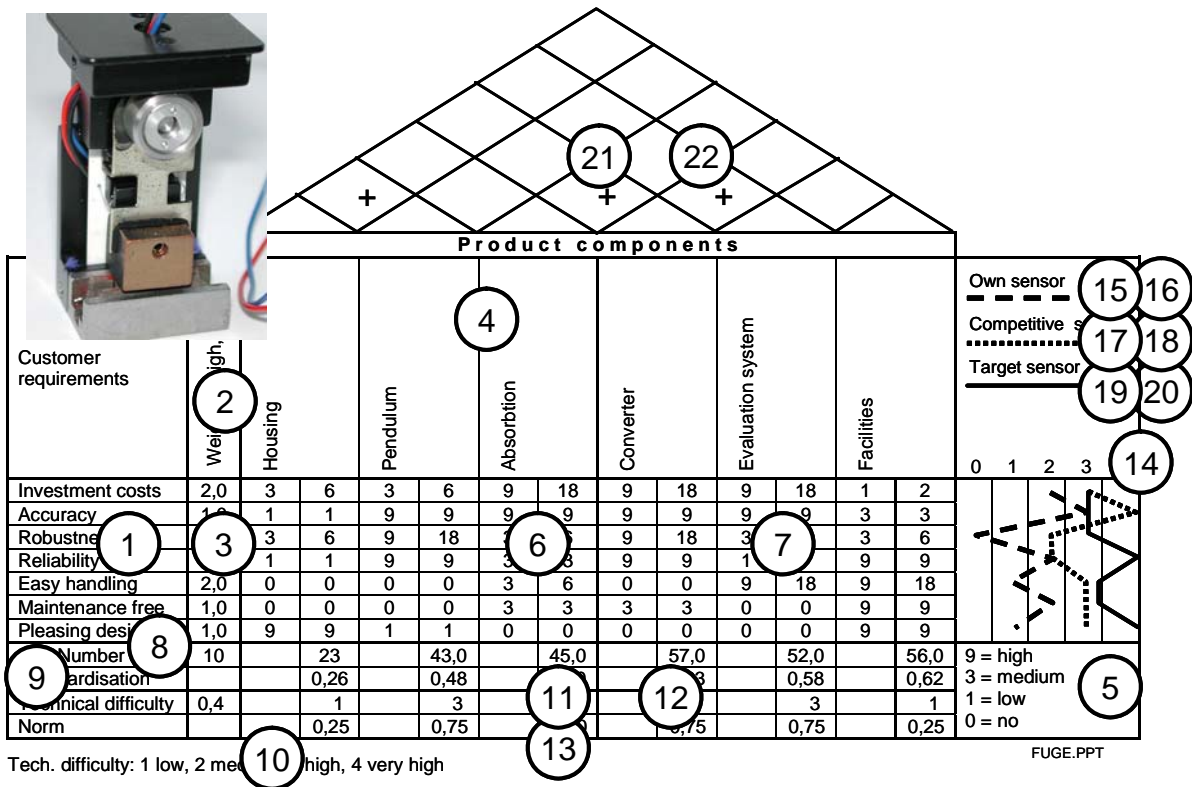


Figure 4: Detailed Quality function Deployment (QfD) for a mechatronic sensor

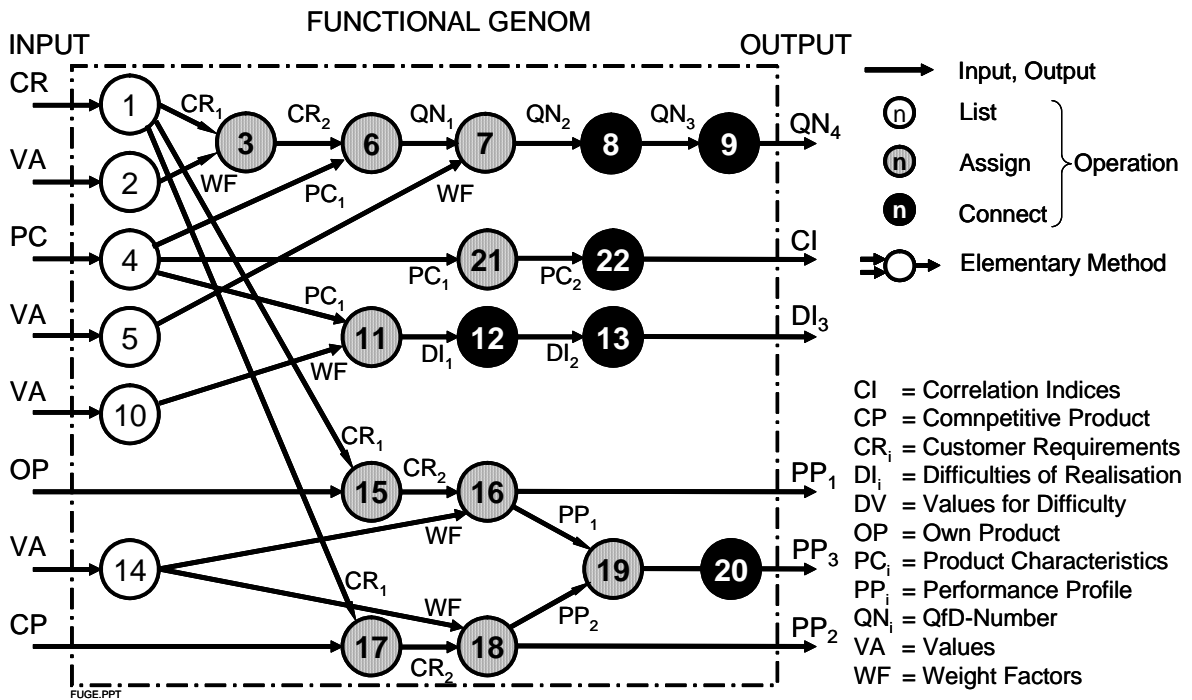


Figure 5: Functional Genome of the QfD according to figure 4 composed by elementary methods (presentation simplified)

Regarding figure 5 some specialties in regard to operations and elementary methods attract attention:

- The very first operations on left hand side are *List-operations*, which create the starting point of following procedures
- In the centre we see throughout a number of “Assign”-operations which link the input elements in specific, goal-oriented relations.

- Right hand side the assigned listed are processed and new information is created and presented as output.
- The HoQ uses 4 *List*-operations to define value-lists (no. 2, 5, 10 and 14) and 5 *Assign*-operations (no. 3, 7, 11, 16, 18) linking elements with weight factors, which indicates the assessing-character of this method and probably some kind of dependency of individual estimations.
- Surprisingly no *Divide*-and *Merge*-operation are used in HoQ. In consequence the very nature of HoQ is not to structure but to process information.

These and further findings represent the fundament for reasoning the application and benefits of the list-approach in next chapter.

5 APPLICATION AND BENEFITS

Even if the elaboration of the approach is still in progress, the results so far are promising for design research as well as for design practice.

5.1 Classification and typology of design methods

The major part of the analysed design methods belong to the design phases “Clarification of task” and “Conceptual design”. However, it is already obvious that most current design methods as well may be reduced to a limited set of elementary methods. It was already proven with methods from other design spheres like QfD, FMEA, Eco-Indicator, Design for Experiments, Cost Calculation Methods and Value Analysis. Based on this fact, it is easy to see the "parents" as well as the "children" of a design method by comparing the shared genomes. Just the same, it should be easy to detect similarities and differences between different design methods by comparing the particular genomes.

In addition one may now assess the level of difficulty of a given design method. If elementary methods are assessed due to their origin level of difficulty, than the level of difficulty for a given method may be estimated according to the equation

$$S = \sum (A_i \cdot s_i) \text{ with}$$

S = level of difficulty of a complex method

A_i = Number of a specific elementary method occurring in the sequence

s_i = level of difficulty of a elementary method

i = Index for each of the 5 elementary methods

As a first result, about half of the analysed design methods were calculated (table 2).

Tab.2: Rough estimation of the level of difficulty of some design methods [3]

Design Method	Level of difficulty
Use of Checklists	2
Use of Design Catalogues	3
Morphological Box	3
Intuitive Evaluation of Solutions	4
Compatibility Analysis	5
Functional Decomposition	7
Goal conflict analysis	7
Weighted Paired Comparison	9
Selection list	9
Eco-Indicator 95	11
Requirement List	13
Function Costs Analysis	14
Kano-Analysis	17
Quality function Deployment	22
Systematic Product Evaluation VDI 2225	34
Failure Mode and Effects Analysis (FMEA)	41

This estimation does not take into consideration the amount of work to carry out a specific application. Rather it indicates how difficult it is to capture the method.

5.2 Flexible adaptation of design methods

With the genome-concept of a specific method, it seems to be quite easy to change it to fit a specific design situation. Now the whole range for reducing and enlarging a given design method can be seen and directly used for a flexible adaptation of methods to a specific design environment. In this sense, a “Minimum-QfD” is nothing else than an elementary method, which directly links product components to customer wishes according to the related importance. Each stage from a Minimum-QfD over the standard one to an extended QfD is in the end nothing else than a question of reducing or enlarging the genome. Figure 6 demonstrates three examples of a specific mixture and enlargement of HoQ-subgenoms according to a specific design task.

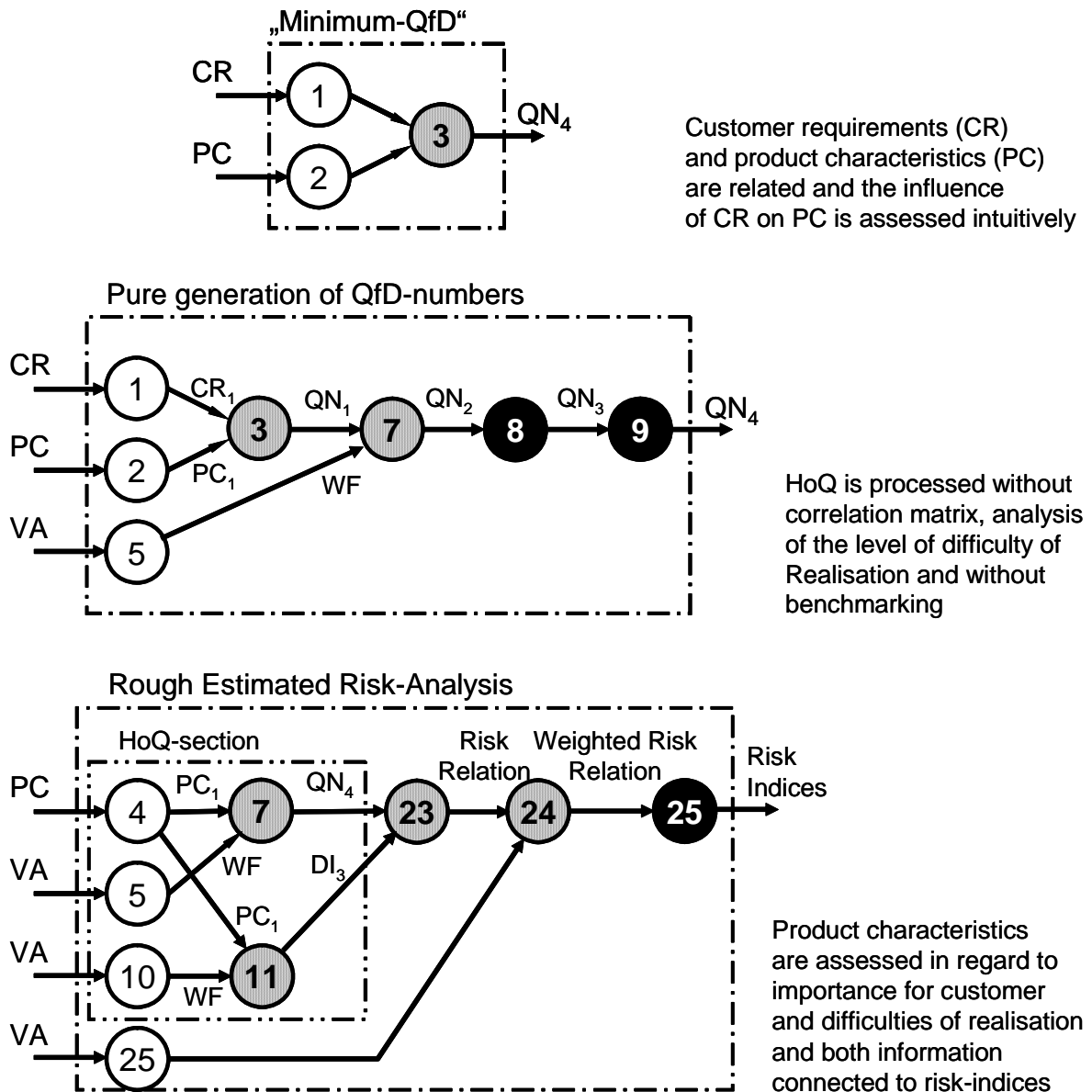


Fig 6: A set of different QfD with its genomes reduced for creating specific outputs

As the research work on elementary methods is ongoing, it is hard to anticipate the benefit for education and training at this time. Nevertheless, one has to be aware of the promising perspectives for a deepened insight into the working principles of a design method and in consequence for its professional use due to the flexibility of linking related elementary methods.

5.3 Semi-automated generation of a method description

The proven “Process-oriented Method Model” (PoMM) can also be used to support the description of a flexible generated design method. Supposing the approach describing the whole set of elementary methods in the “signature” of PoMM, one may use this description quite effectively and efficiently. If a specific design case needs a more complex method (container), the different PoMM-descriptions of the relevant elementary methods can be easily overlaid. By doing this, one will inevitably get a complete and probably well-founded PoMM of such method. This approach does not need the existence of predefined method descriptions but generates a specific description of a complex method from a limited set of description of elementary methods.

5.4 Automated generation of an appropriate design method and its description

Conversely, the characteristics of a specific design project may be compared with the prerequisites of elementary methods. If the available input, the desired output and the design environment or situation are known, there may be a vision that a “Method Creating Tool” will create or at least suggest an appropriate method with its description more or less automatically. This vision is partly realised in the so-called “*Dynamic Process Generator*” of the *pinngate*-navigator [17], which creates process chains automatically out of a set of given process modules, if inputs and outputs are defined. Combined with the standardisation of method description in the PoMM-approach a powerful tool may be developed in future, to support design practice substantially with a design environment specific *Method Creator*. A first tool [3] using the list approach was developed to test its applicability.

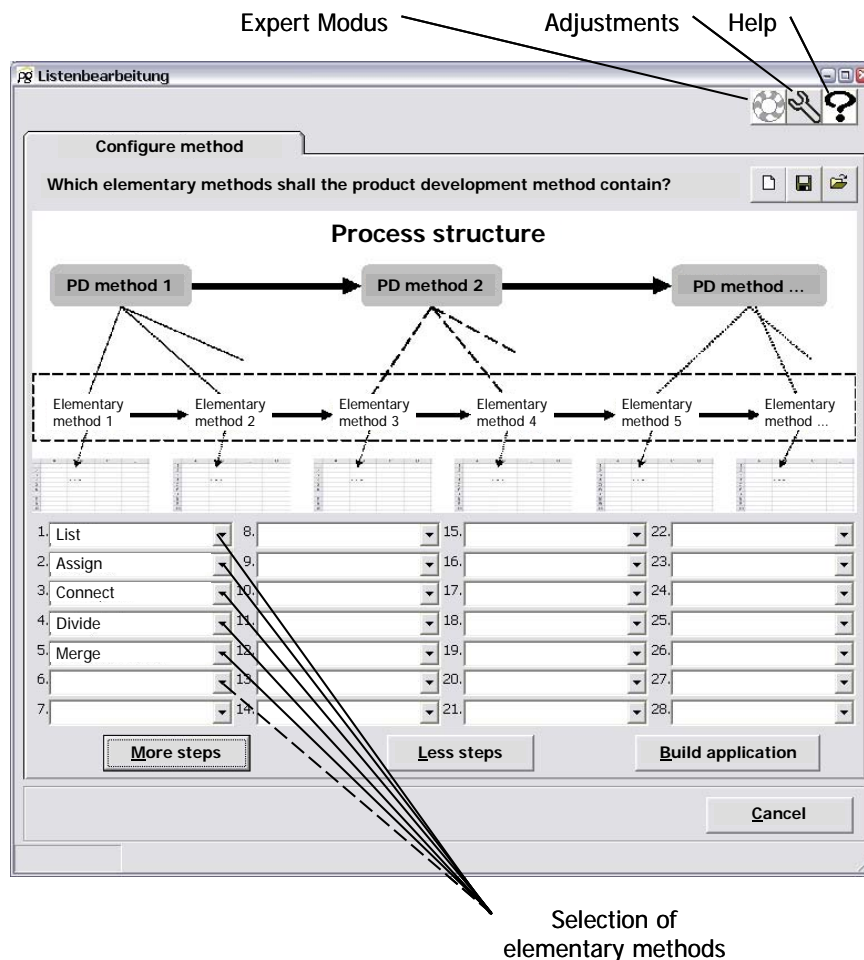


Fig 6: Screenshot of the tool for evaluating the list-approach

This tool is expected to prepare the semi-automated and even automated generation of an appropriate sequence of elementary methods and to test the import and export of objects and knowledge stored in the *pinngate*-modules (figure 6).

6 CONCLUSION

The list-approach in order to defining elementary methods has proven powerful in systematising existing and creating adapted design methods [3]. The clear definition of elements and relations and the obvious derivation of the elementary methods reduce or even avoid interpretation problems arising from different views and meanings. The benefits of these elementary methods for science, research and practice are obvious, even if research is ongoing. The remarkable success of the approach so far shows that it most likely satisfies a specific element of human communication. It seems that the linking of elements with relations is a commonly used and powerful procedure to transmit information from one person to another.

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