Applied Engineering Design Science - The Missing Link between Design Science and Design in Industry

Prof. Dr. h.c. Dr.-Ing. Herbert Birkhofer and Dipl.-Ing. Martin Wäldele

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1. Introduction

Since the mid-1960's, where current design research has its origins, a vast amount of knowledge, methods and tools has been elaborated upon by design researchers. The main focus of research was on the early phases of design work, and especially the development of the phases "clarification of the task" and "conceptual design". Recently, however, in researching the phase of embodiment design, limitations in regard to generalisation become obvious. Knowledge, rules and methods differ within branches and product types and greatly depend on characteristics such as function, size, material and complexity of products or the type of manufacturing process. The use of generalised design support therefore decreases dramatically in the "later phases" of product development (detailed design, testing, planning of manufacturing and assembly processes, quality control), where we find a variety of partially extremely specialised methods, not at all linked to the principles of design science. This paper deals with the approach of *Applied Engineering Design Science (AEDS)*, which may be seen as a special type of design research supposed to overcome the barriers mentioned before.

2. The Body of Development Knowledge

2.1 Design Science

In a holistic view one may regard the entirety of knowledge used in all processes of product development as a body of development knowledge (figure 1).

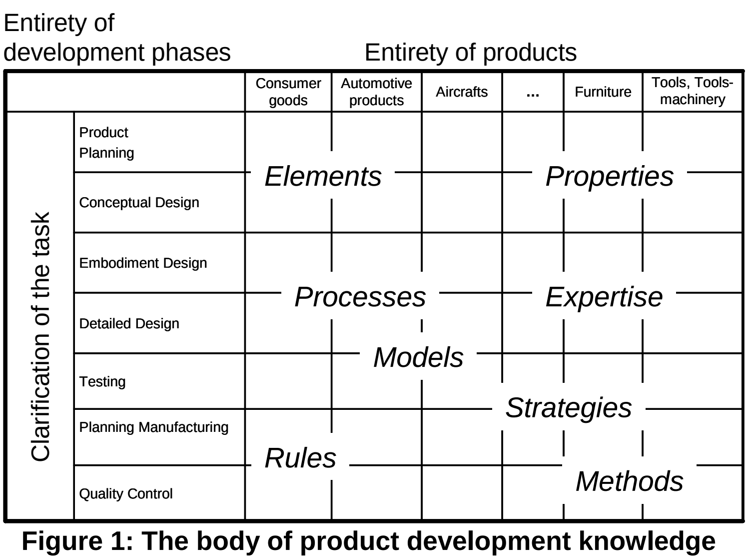

Figure 1: The body of product development knowledge

The term "knowledge" is used here to contain specialisations like expertise, methods, rules or tools, which refer to product development and give adequate support. Within product development the design processes, focused on the concretisation of product models, take place and are supported by design knowledge.
It is the nature of Design Science to focus on the generalisation of Design Knowledge throughout all branches and products. General characteristics of different technical systems are elaborated by means of abstraction. A typical representative of such a generalisation is the model of General Functions [Roth 2000], which may be used to describe input-output-relations within all technical systems transforming material, energy or information.
Within Design Science most important generalisations are carried out in the form of product models, which represent specific properties of technical systems. The Model-Pyramid (figure 2) visualises the product models used in Design Methodology [Sauer 2003].

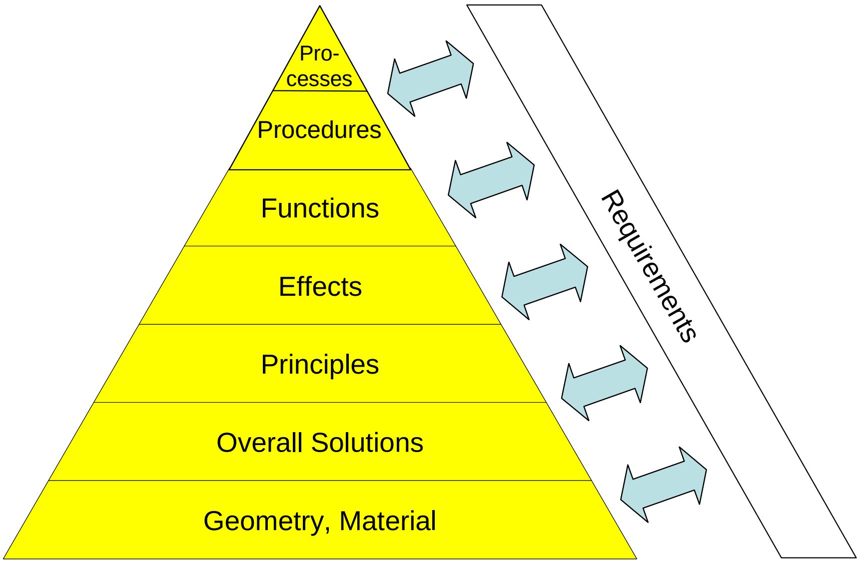

Figure 2: Model Pyramid of Technical Systems

The pyramid shape indicates the increase of product properties from top to bottom linked to different models. Within design work designers have to adjust requirements formulated at the beginning of design work to the product properties represented by a particular model.

2.2 The Horizontal Approach of current Design Science

Current Design Science focuses on the generalisation of Design Knowledge and tools preferably in the early phases of design throughout all branches and products. This resembles a “horizontal approach” of design entirety, which covers functional and principal properties of Technical Systems (figure 3).
A major benefit of such an approach is that it points out the similarities of systems e.g. in regard to functions or working principles. Such a generalisation supports the understanding especially in teaching and education and seems to be of greatest importance in overcoming a purely isolated view of specific products or components, which is often observed in design practice.

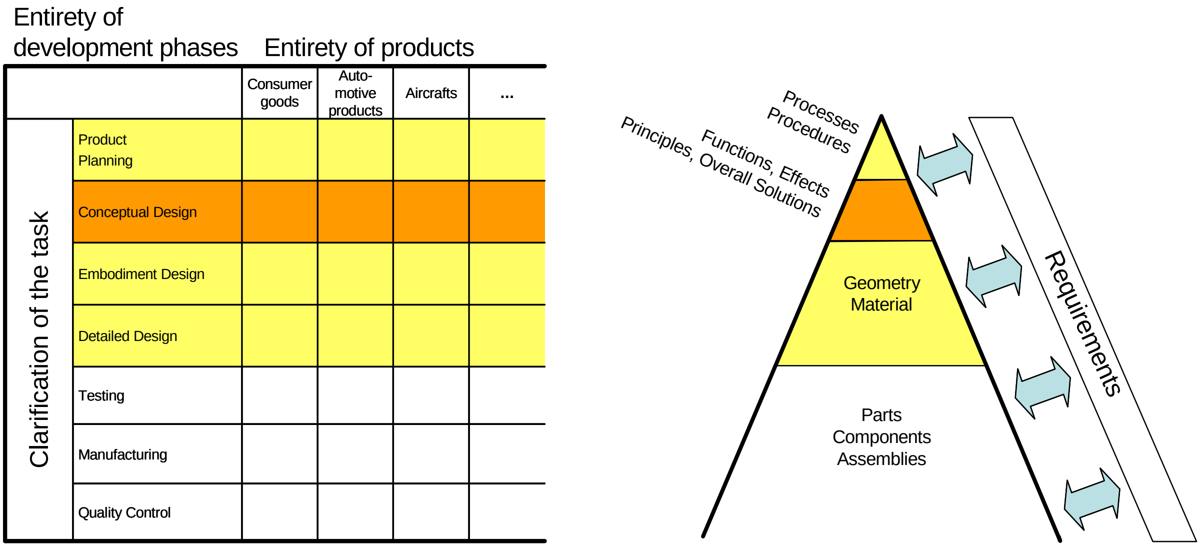

Figure 3: The horizontal approach of current Design Science

Nevertheless, a generalisation approach covering the entirety of Technical Systems is limited in regard to supporting design understanding and design work:

- In later phases of design, the number of product properties and the number of relationships between properties increase progressively. A generalisation will either fail due to the huge amount of properties or be more or less useless due to its high level of abstraction.
- Concerning the definition of geometry and material for a single part only, there are many influencing factors to be taken into consideration for a proper design. Additionally, one needs much expertise specific to a branch, a manufacturing type or even a company. General rules for determining the shape of a part, like the well-known good-bad-examples for Design for Manufacturing, seem quite artificial to a designer, who is struggling with a specific design task like the low-cost-design of car gear housing.

It is no surprise therefore, that current Design Science mostly covers the early phases of Design, where abstraction is quite useful and that the majority of Design Research contributions deal with the conceptual phase or the first steps of Embodiment Design.

2.3 The Vertical Approach of Applied Engineering Design Science

To step up to a Design Science, covering all phases of development work with the same level of intensity and offering the same amount of support to designers throughout the entire development process, a “vertical approach” is required, intended for Applied Engineering Design Science (AEDS) and demonstrated in figure 4.

AEDS generalises the knowledge used in a specific branch for a specific product type or process chain throughout all phases of product development. This “vertical approach” takes “scientific responsibility” for supporting the whole development process. It could be compared to the “practical responsibility” of a project leader, who has to supervise the entire product life from customer and market requirements to after-sale services. In other words: AEDS has to provide general methodical support in developing a product in its lifetime.

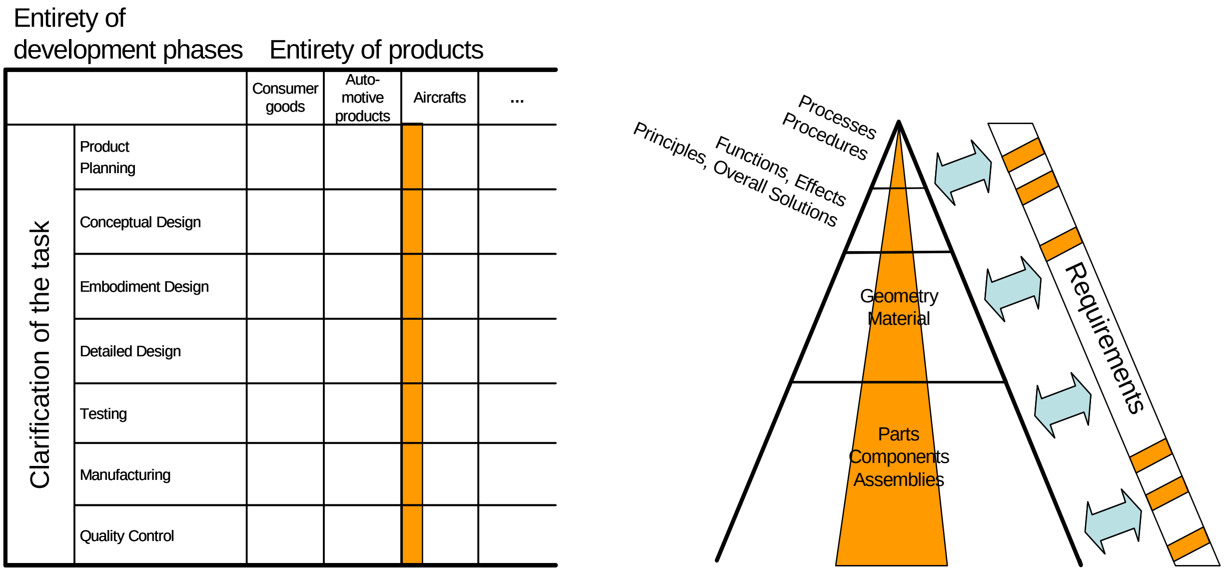

Figure 4: The vertical approach of Applied Engineering Design Science

2.4 An attempt to conceptualise Applied Design Science

AEDS should be something between the extremes of the very general knowledge of Design Science and the much focused knowledge of a specific design work (e.g. design of a turbine blade for an Airbus engine). Even if it seems problematic to define AEDS by means of products, product classes or branches, a first attempt may produce basic requirements for AEDS:

1. AEDS should be based on the principles and concepts of General Design Science, like product-process differentiation and product-properties relation.
2. AEDS should offer substantial support throughout the whole process of product development, which includes support for the management of information, the application of methods and the use of tools.
3. The management of knowledge has to cover the whole product-lifetime. Also, information about after-sales services and recycling/disposal has to be integrated into information management.
4. The application of methods must, of course, integrate conventional design methods like requirement lists or Morphological Boxes as well as so called “Bypass-Methods” [Birkhofer 2005], which have their origins outside Systematic Design. Quality Management, Statistical Test Planning or Simultaneous Engineering are widely used in design departments and therefore have to be a part of AEDS
5. As with methods, tools like FEM, CAD, PDM and simulation tools should also be integrated in an AEDS-Methodology. They produce valuable results for managing and improving products and processes during design work and often are related, but not linked together.

As most of the methods and tools are produced isolated from each other, a major task for AEDS seems to be to harmonise and even to clean up the body of knowledge within a specific area of application. The widespread fragmentation of methods and tools currently used in design departments must be seen as one important reason for overloading and even frustrating designers.

The future of design work should end up in a parallel treatment of product properties like functionality, costs and quality, which means the adaptation of general methods to the specific product requirements as well as the harmonising of related methods like methods for the management of cost, quality or environment.

3. Specification of generalised methods for profile structures

3.1 A new technology to produce profile structures

The AEDS-concept, in regard to a consequent Life Cycle Design, is illustrated in this paper and partially demonstrated by the example of the development of bifurcated profiles. These profiles were manufactured in a new forming technique called “linear flow splitting”, elaborated at Darmstadt University of Technology. Linear flow splitting is a new massive forming process for the production of bifurcated profiles in integral style. The semi-finished part is a plane sheet metal which is transformed at an ambient temperature by a specific tooling system, consisting of obtuse angled splitting rolls and supporting rolls. The fixed tool system forms the translative moved work piece in discrete steps up to a bifurcated profile. This innovative technique was the seed for the Collaborative Research Centre 666 (CRC 666), which focuses on the optimisation and algorithmisation of the complete product development process for profile structures (figure 5).

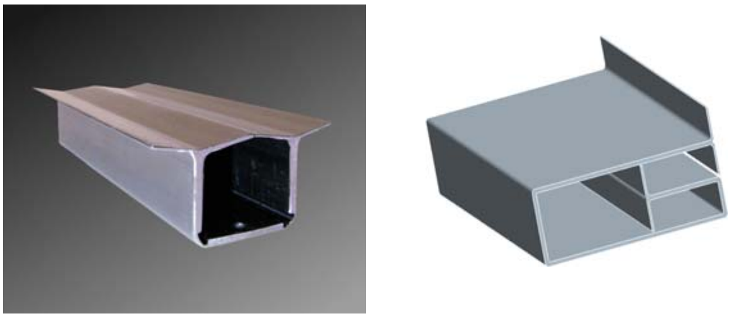

Figure 5: Possible Profile Structures made by Linear flow Splitting

3.2 The AEDS-approach for designing profile structures

Concerning the use of product models within the Model-Pyramid, they have to be adapted in the AEDS-approach to certain applications for specific branches. Adaption means either a limitation on specific models out of a set of general models or the concretisation of general models to specific needs.

Figure 6 demonstrates the AEDS approach related to requirements for profile structures manufactured with the new forming process. Of a variety of requirements only a few are of interest for profile structures made from sheet metal. Other requirements such as ergonomically demands are less relevant. Because of the limited spectrum of requirements, it will be easier to create standardised sets of requirements and demands for such profiles as well as to offer checklists for drawing up a requirements list.

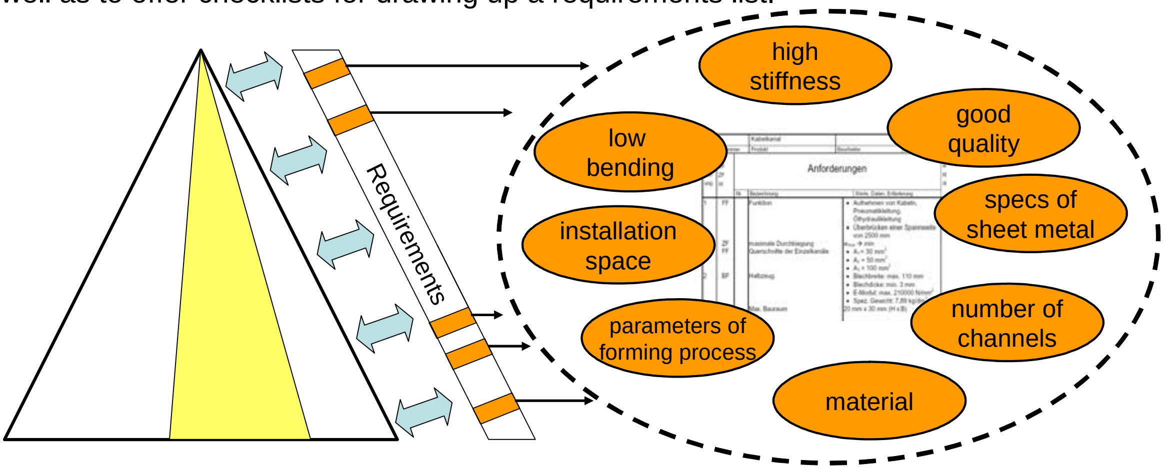

Figure 6: Standardised requirements for profile structures

For a functional view on profiles made of sheet metal, it is easy to reduce the general functions for this special field of application. In such profiles it would be rather unusual to have any signal in- or output, so these functions have not to be regarded by designers. In the majority of cases profile structures use functions such as store material, guide material or energy (figure 7).

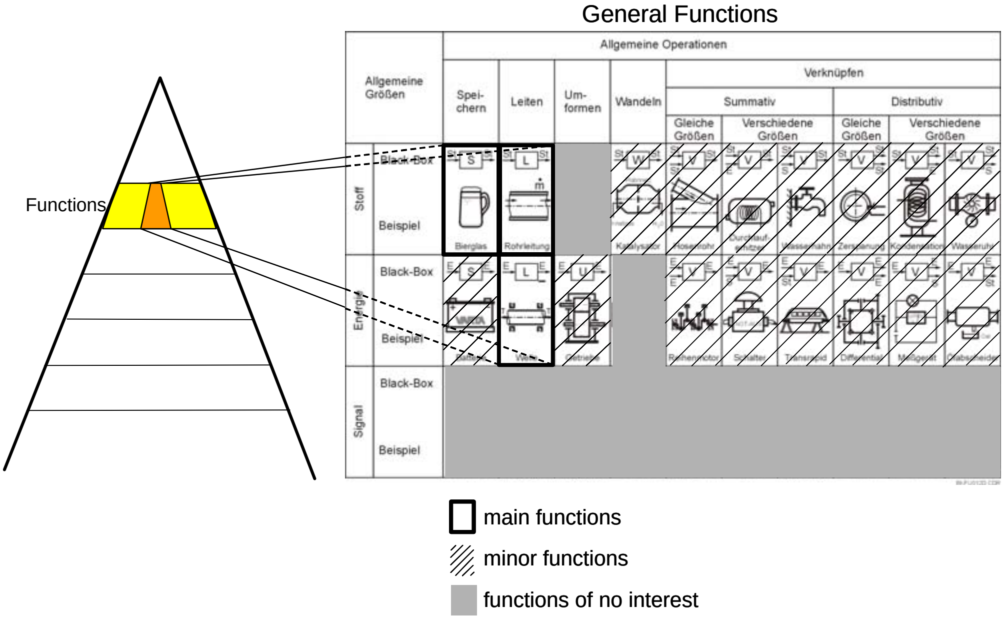

Figure 7: Specification of General Functions for profile structures

Same at functions, the number of effects in nature and working principles to fulfil certain functions is limited to those realising the mainly used functions. To resist mechanical loads like forces and moments profiles “use”:

- the physical effects of elasticity and stability
- the working principle of a beam, supported at both ends

As there is a strong hierarchic interrelationship between the models of the Model-Pyramid, a limited number of abstract models used in a special application leads to a remarkable reduction of later used models. Additionally, requirements have to be taken into account only for this limited number of effects and working principles, which reduces the design effort dramatically.

In the later phases of the Model-Pyramid the geometry of parts and assemblies have to be defined and modelled with 3D-CAD programs. For the application on the design of sheet metal profile structures specific features and functions can be implemented in a CAD workbench. Those features and functions, like a cutout at the edges or reinforcing rip structures, have to be made available to the designer (figure 8).

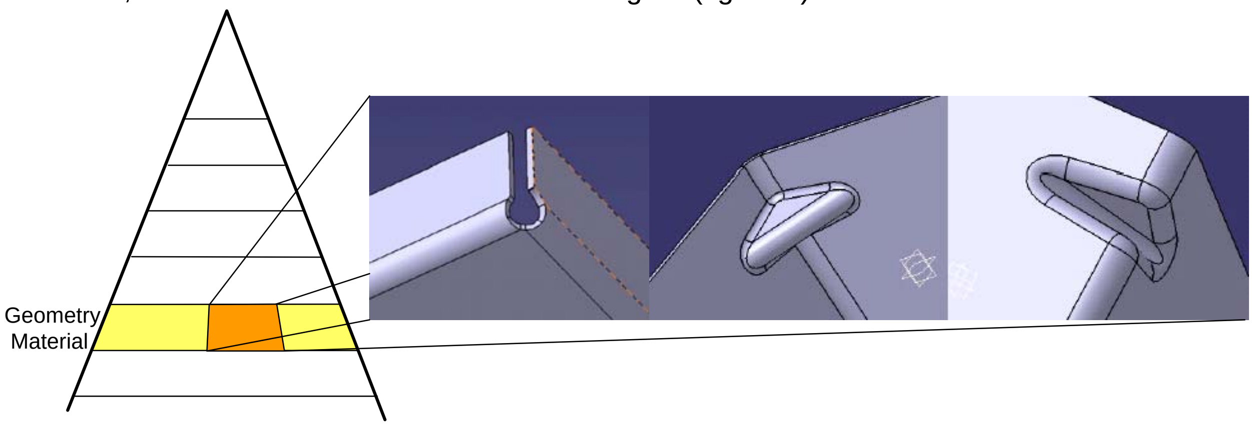

Figure 8: Specification of 3D-CAD systems for profile structures

It is obvious, that design science may succeed to create an efficient modelling strategy to give a guideline how and in which order the design of those sheet metal structures can be done best.

4. Current and future development of AEDS

4.1 Applied Design Science supporting human problem-solving

An efficient and effective AEDS-approach should be based on a systematic design procedure starting at an abstract process and functional level and proceeding to a concrete product model with specific geometry and materials. Using the product model pyramid, the design procedure may be regarded as a progressive enrichment of product properties according to the respective product model. This product modelling has to be to be carried out in parallel to a process modelling for all processes in the product lifetime like processes for testing, manufacturing and service [Abele 2005].

This procedure has been presented in literature since the evolution of systematic design and is adapted to the problem-solving processes of human beings. In dealing with the abstract, vague and incomplete set of product models designers have to be aware of the cognitive limitations of human thinking. Therefore a step-by-step procedure with enrichment of product model properties followed by selection, evaluation and decision procedures has proven a most suitable approach to handle the early phases of design.

4.2 Applied Design Science based on a computer-aided approach

In comparison to the step-by-step enrichment of product properties over the different phases of the Model-Pyramid, a new algorithm-based approach is introduced (figure 9).

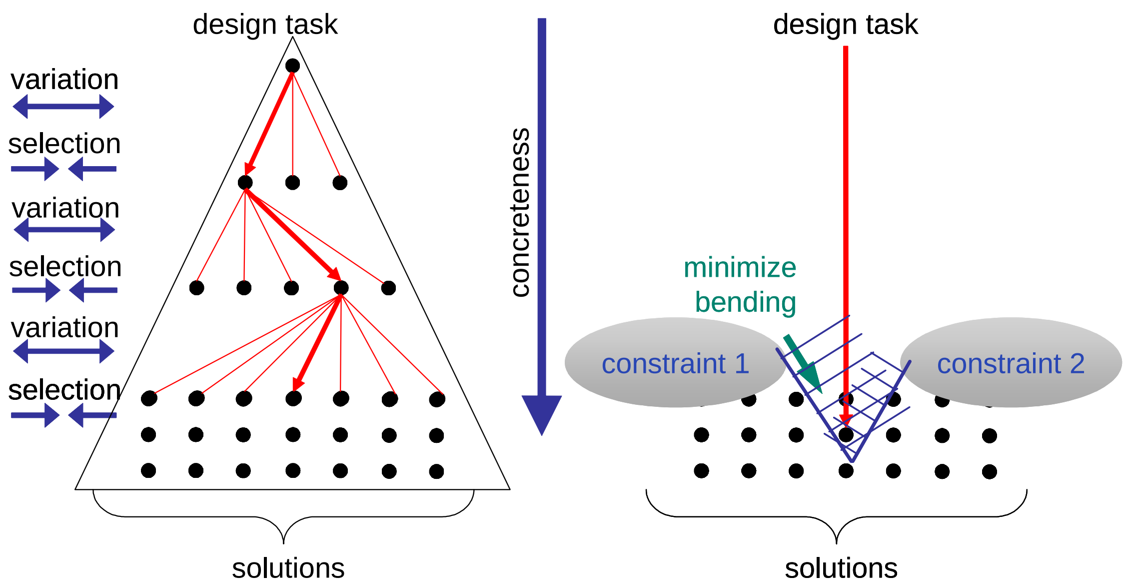

Figure 9. Conventional Product Design and the "New Approach"

Both approaches, conventional product design and the "new approach", start with the clarification of the design task. Conventional product design is a process of variation and selection over different phases by adding product properties with every step and becoming more concrete.

The main focus of the "new approach" is to elaborate the customer- and market requirements just for the specific branch of profile structures in such way, that a mathematical optimisation process can follow. A fundamental prerequisite for this approach is the limitation of requirements and models for a specific product type or branch according to AEDS.

Doing so, vague costumer requirements have to be altered into a standardised set of requirements. From this standardised set of requirements, the product properties desired by the customer must be transformed. They are called "outer-properties" (e.g. “low bending”) [Hubka 1996]. These outer-properties cannot be established in a direct way by the engineer. The designer has to choose parameters, so called inner-properties, which are related to the outer-properties and which can be established in a direct way (e.g. material or geometry parameters). In short: The designer has to choose inner-properties in such a way that the outer-properties are met.

In mathematical optimisation, product properties can be understood as constraints and objectives. In Figure 9 the black dots represent the whole field of different solutions. Constraints reduce the field of different solutions and define them. Solutions that fulfil each of the constraints simultaneously can be considered as a feasible solution for the design task, posed by the hatched space in between constraints 1 and 2. If the feasible solution is not unique, all feasible solutions can be evaluated by objective functions (e.g. low bending), which will lead to the best solution for the design task.

5. Summary

In preparing CRC 666 for almost two years, much experience and knowledge regarding the framework of AEDS has been derived:

- The basic principles of Design Science are a reliable fundament for the systematisation of elements and relations, not only in design but in the entirety of product life processes.
- A variety of methods used in different phases of product life, such as product planning methods, design methods, quality control methods or methods for estimation and calculation of costs can be reduced to a limited set of “adapted methods” or supplemented by a specialised set of methods which can be used only in specific branches.
- An algorithm-based design, which is the objective of CRC 666, requires a highly formalised “Design Language” based on the terms and definitions of Design Science. However, the effort to "motivate" designers to use this exactly defined “Design Language” in their daily work is problematic. Designers are human beings possessing creativity and individuality, who need freedom development within the specific design area. In addition, research in cognitive psychology is demonstrating the power of vague, roughly defined terms for breaking out of fixations and generating creative design.

If AEDS can be seen as a new and prospering area of design research, the most challenging task should be to use the specialised expertise, methods and tools within the often very specific environment and vocabulary of branches, companies and products, as well as to raise support for well- and even rigidly defined fundamentals, which have been elaborated in design science for a long time.

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