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DESIGNING THE SOLUTION SPACE FOR THE AUTOGENETIC DESIGN THEORY (ADT)

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1. Introduction

The Autogenetic Design Theory (ADT) uses analogies between natural evolution and product development to ensure that the best possible solution can be found within given requirements, conditions, and boundaries [Bercsey and Vajna 1994] [Wegner 1999] [Vajna et al. 2005]. These requirements, conditions and boundaries can also contradict each other and can change over time, i.e. "best possible" has always to be interpreted in relation to the actual situation. The ADT describes the development of products as a continuous improvement and optimisation process. The presence of self-similar activities at all levels of design efforts and the existence of chaotic behavior are characteristics of the ADT.

As it plays a crucial role to the succes of the ADT, it is necessary to find appropriate strategies and approaches for describing and searching the solution space, which allow representing dynamic requirements, conditions, and constraints, in order to assure the exploitation of all potential solutions as complete as possible. The research findings on the design of an appropriate solution space for the ADT are the focus of this paper.

2. Autogenetic Design Theory

The main thesis of the Autogenetic Design Theory is that the procedures, methods, and processes of natural evolution to create or to adapt individuals are analogous to the procedures, methods, and processes of developing products. Consequently, the ADT transfers procedures, methods, and processes from natural evolution to product development with both its emerging products (including their properties) and its environment of requirements, conditions, boundaries, and constraints. One main characteristic of natural evolution (with the underlying principle of trial and error) is continuous development and permanent adaptation of individuals with minimal use of resources to changing targets that are dynamic because of changing requirements, conditions, boundaries, and constraints. All these can contradict each other and can change over time. This suggests that both evolution and product development can be described as a continuous improvement process or as a kind of optimisation. Further characteristics of the ADT are the presence of self-similar activities and the existence of chaotic behaviour.

In evolution, the methods for creating or adapting individuals are determined by evolutionary operators. These are replication, mutation, recombination, and selection. Replication results in an identical copy of an individual. Especially the mutation (of which outcome and occurrence aren't predictable) leads to new ideas, insights, or unexpected solutions. The recombination is the combination of (usually two) different already known principles to create a new solution. The selection is the operator for selecting appropriate solutions from a given set of alternatives.

One may argue that a weakness of the ADT is a result of this evolutionary based approach, because, for reaching a certain quality level, a high number of individuals need to be evaluated. Compared with

other methods, the number of solutions, which need to be evaluated, is much higher. But one has to keep in mind that, by exploring this high number of possible solutions (individuals) within a solution area that adapts to possible changes, the chance of finding the really best solution to a given set of requirements, conditions, boundaries, and constraints is much better than with traditional approaches that continuously delimit the solution are and that result in a single next best solution.
The analysis of product development from an evolutionary perspective leads to the following insights:

- In every phase of the product development process, various alternatives are developed and compared. These alternatives are in competition with each other, because only the best were selected for further processing.
- The processes of searching, evaluating, selecting, and combining are also typical approaches of natural evolution.
- Regardless of the phase of product development or of the complexity level of the emerging product, always a similar pattern of activities is used to generate new solutions, which is comparable with the TOTE-Scheme [Miller, Galanter, Pribram 1991] [Ehrlenspiel 2007]. Self-similarity can be found at all levels of complexity of product development as well as in all stages of the emerging product [Wegner 1999].
- According to chaos theory small changes or disruptions in the system can cause unpredictable system behaviour [Briggs and Peat 1990]. The fact that the result of the development of a product usually can't be predicted definitely because of the influence of the creativity of the product developer, leads to the assumption that the product development process also contains elements of a chaotic system or at least shows a chaotic behaviour in some aspects.

At the present state of the ADT research, an evolutionary product development can be described as a complex dynamic network over several levels of product and process complexity. This development is characterised by the evolutionary operators replication, recombination, mutation, and selection at all levels of complexity. At all levels self-similar actions take place. Thereby, only those properties where handed over to the successive solutions, which satisfy the prevailing requirements the most accurate at a particular point of time. This so-called autogenesis (self development) is recognisable in the creation of any (partial) solution, because any solution must go through this process. The goal of the optimisation itself may change, just like the (usually dynamic) environment.

3. The ADT Solution Space

Like every other development method, the ADT needs an area from which possible solutions can emerge. In earlier research [Kittel and Vajna 2009] it was found that the solution space of the ADT is defined and structured by current requirements as well as initial, boundary and constraint conditions. Evolution takes place within this solution space. It was further determined that the solution space can contain solutions of varying quality, including the so-called start objects (equivalent to the "first population" in biological evolution) that are generated either randomly or from previous solutions, part catalogues (e.g., screws according to DIN 912), design catalogues, kits, advanced features, solution elements, etc, or combinations thereof. Furthermore, existing solutions may be available that were not used for the current requirements.
In general, the term "solution space” is understood to be a set of all feasible solution elements, which can be used for the development of the requested solutions. This includes all of those elements that a product developer may use for the evolution of a solution or several solutions, on the basis of requirements, inner and outer conditions, ecological/environmental conditions and others. The definition of solution space given here can be compared with the mathematical term “domain”. The goal behind this concept is to narrow the number of solution elements, until only one final solution exists.
In the current state of research, the ADT solution space contains solution elements in the form of given or required product criteria (those product properties, which are relevant for a decision during a selection process between different product alternatives) and design parameters (parameters that significantly influence product characteristics). Solution elements contribute directly or indirectly to the embodiment of solutions, depending on their type and severity. They can also be formulated as specifications for the resulting solutions that can be available in any specific configuration or

combination. Since existing (partial) solutions for configurations, combinations, and relationships of solution elements among one another can be described, so can the (partial) solution components of the solution space. Relationships can also contain multifaceted relationships to one another, which can be described with rules (sharp or fuzzy). Not only geometric solution elements can be described, but as well elements such as materials, work methods, manufacturing methods, tolerances, surface finishes, etc, independent of whether they exist in fixed or parametric forms.
The structure of the solution space allows a flexible formulation of requirements in terms of required criteria and design parameters with any number of configurations, combinations, and conditions. In such a solution space, a solution arises from a selection, configuration, and combination of solution elements. Becoming more and more similar, although not equivalent, solutions will be aligned along a Pareto front. With the setup of a solution space for a specific task, it can be assumed with all likelihood that only subsets of all of possible configurations, combinations, and relationships of the solutions elements will be available in the solution space. Evolution, for example, can then take place through new (but acceptable) combinations of known (partial) solutions for a new product.
The solution space of the ADT contains the possible solution elements at a certain time in the development process. An important feature of the ADT is that its solution space dynamically changes as soon as an external event (for example a requirement modification, a change of a condition, etc.) occurs during the evolution, because, as a result of this external event, new or other possibilities for the evolution can arise or existing ones have to be omitted. To reflect these, the solution space has to be re-designed. This can be of any kind, e.g. other boundaries, an enlargement, a shrinkage, a re-structuring, etc. After each such change, it is imperative to re-extend the search to the entire "newly designed” solution space in order to get now all those solutions that take into consideration the actual conditions (Figure 1).

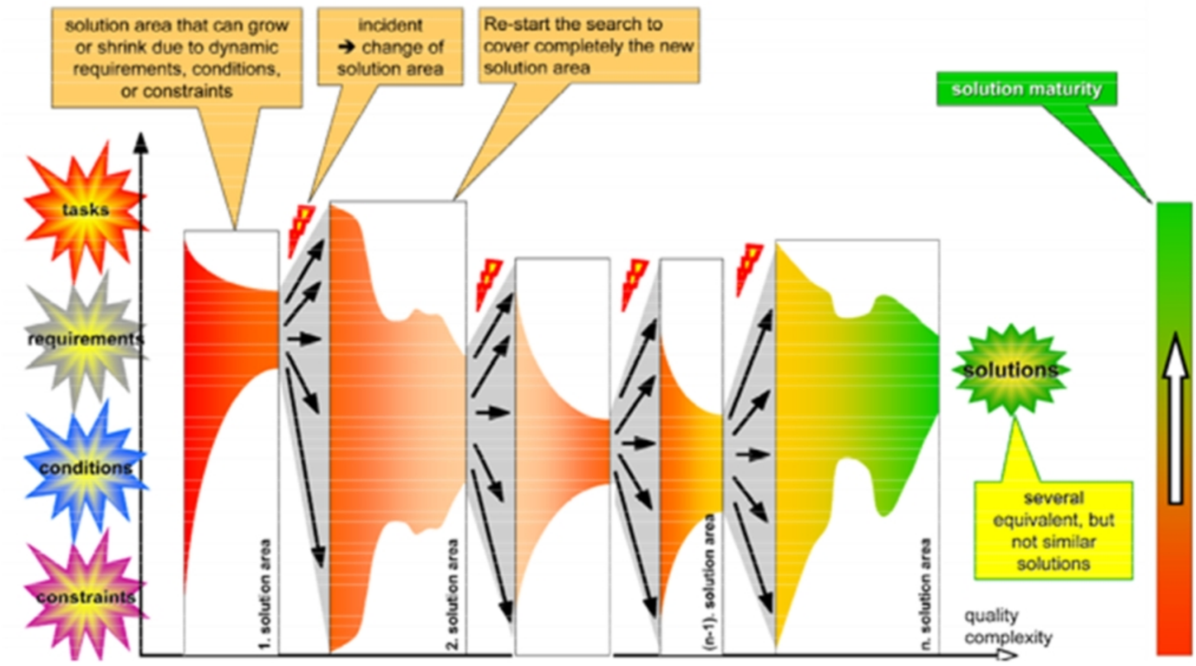

Figure 1. Changes of the Solution Space

In the following, solution space variations are presented that were developed especially in consideration of an unrestricted generation of solutions. The solution space should be provided in a way that the product developer will not be limited by an incomplete or overly limited solution space.
First of all, the interaction of a solution space and the resulting solutions (= individuals) within biological evolution is presented. While the biological solution space with regards to the different conditions and their relationships with one another behaves essentially the same way as the aforementioned description, the solution elements for the formation of individuals are developed extremely simply. The genetic information of an individual is stored in the double helix of

deoxyribonucleic acid (DNA) in individual genes. Every individual is described through his or her genes. All genes are ultimately composed of combinations of the four organic bases adenine, guanine, cytosine and thymine (A, G, C and T). Via the number, arrangement, and relationships of these genes in the DNA, it is possible to create plans for all individuals.
Figure 2 shows the relationships of product criteria and design parameters within the ADT solution space as the result of the (usually) huge variety of influences and impacts of requirements, starting and boundary conditions, constraints, and the respective environment (symbolised by the small vertical ellipse collecting the arrows). As it has been mentioned, the relations between these are far from being simple or linear, in fact, they form a complex network dependent from each other (as described e.g. in [Dünser 2004]). In this example, the product developer would like to influence the criterion "product's weight". As mentioned above, the criterion (weight in this case) cannot be directly specified, but rather arises from a design parameter or a combination of several of these, which contain the allowable options and range of values. In this example, the relationship between design parameters (material and volume) and criterion (weight) is straightforward and analytically calculable for structures that are not too complex. These relationships are not often directly visible for other criteria (for example, accelerations occurring during a car crash).

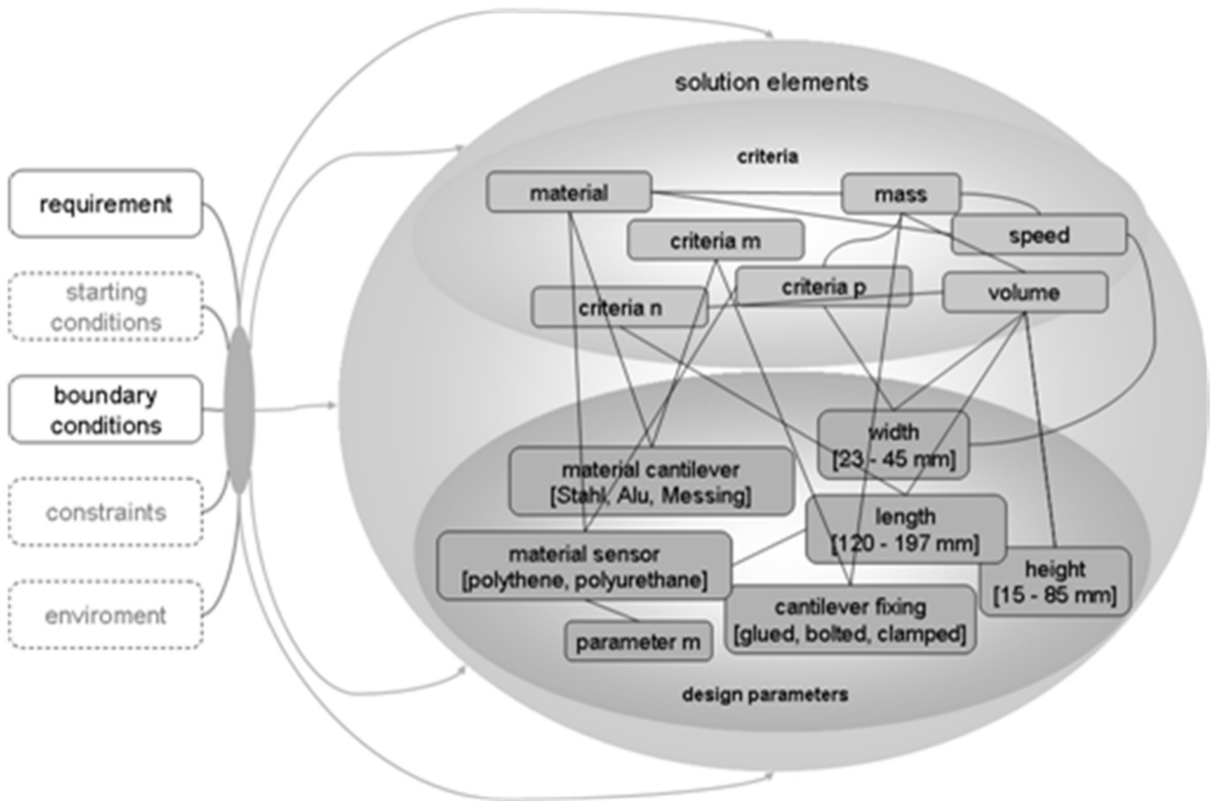

Figure 2. Solution Elements within the ADT Solution Space

There are product development methods that use solution spaces that resemble databases. Such a solution database contains all elements that can be used by the product developer for the definition of a solution during the development process. For example, active principles ("Wirkprinzipien") or partial solutions are offered to solve a specific problem.
Examples of methods using such solution databases are TRIZ [Altshuller 2003], Gene Engineering [Chen and Feng 2003], and IEED [Fan et al. 2005].

- TRIZ uses 40 basic active principles in order to provide a solution to a specific problem. ALTSHULLER identified these sactive principles through the analysis of 200.000 patents.
- Gene Engineering uses the library of "sophisticated genes", although it is not described in detail what "sophisticated" means. This library is supposed to contain all known principles and effects, and is supposed to be expanded as soon as there are new findings from research and

development. During the development of a product, certain product elements are replaced with those from the database in order to achieve product improvement.

- IEED uses a component library. This is used to transform a concept into a physical structure.

What these examples have in common, is that the achievable diversity as well as the functional complexity of possible solutions are always limited. This is a result of both nature and extent of the database contents, as well as the possibilities for the presentation of these contents. Should the database be inadequately filled or there are inadequate presentation facilities, then the achievable (solution) quality is also limited. The creation of such a database also proves itself to be difficult. In order to give the product developer as much freedom as possible, the database must contain all possible elements in question as well as their allowable configurations and combinations. In view of the diversity of solution principles, materials, manufacturing methods, etc, the goal of a complete definition of a (typically rigid) database structure seems hopeless. In addition, with the implementation of such a database, a workable compromise must be found among storage format, content structure and presentation possibilities, user-friendliness, speed of use, ability to be filled or changed, ensuring consistency, cost of maintenance and upkeep, etc.

The following sections present three approaches for the description of a solution space for products: solution space of permitted production operations, binary solution space, and the prohibition model.

3.1 Solution Space of Permitted Production Operations

In this solution space, a product is not defined by parameters such as geometric dimensions, active principles or materials, but rather through a series of permitted production operations. These operations include procurement, manufacturing, assembly, quality assurance and control, sales and marketing operations. This approach offers the advantage that a relatively large number of solutions can be described with only a few elements in the solution space. The definition of a product is the result of the configuration and combination of various production operations. A series of parameters can be defined for each operation in order to describe each operation step in more detail. Through other operation sequences or different step configurations, a large number of products are conceivable.

The advantage of this approach is that each product is describable, and because of using available operations, producible too. Should the stored operations be customised for a specific company, e.g. an aircraft turbine manufacturer, then the product developer is able to only design products (e.g. turbine blades) that can also be manufactured by said company.

The weak point of this approach is that it is increasingly difficult to apply, as products become more and more complex. Complex products, which must be produced by technologically complex production operations that can originate from any arbitrary domain, require a more extensive description than a simple and purely mechanical product. Furthermore, this approach doesn't allow solutions that rely on production operations that are not already available in the solution space. This means that innovation can only evolve within the context of stored production operations. This problem could be solved by always storing the current state of relevant production operations, independent of whether they are available in the company or not. So products can evolve that fully meet the requirements, but can't yet be produced in the company. In such a case, the company must decide whether to acquire the necessary equipment or to dismiss a high performant product.

3.2 Binary Solution Space

This approach uses the characteristic of biological evolution to describe the genetic information of an indivdual (product) by using only for basic acids, i.e. to provide a solution space with a minimum number of solution elements.

Modern computer systems increasingly offer the possibility to completely describe products (beyond pure geometry). What is interesting about computer generated models of real parts is that they consist of only two components at the lowest storage level: zero and one. This even presents a half of the number of solution elements within biological evolution. Another similarity is that the arrangement of building blocks doesn't exhibit a structure whatsoever, but is rather a series of zeros and ones.

A modelling software (a CAD system, for example) models all representable products with the building blocks zero and one. All products differ in only two points, the quantity of zeros and ones

used and their sequence. Therefore, with only two solution elements, one can describe a disproportionately large number of products.
However, this approach has the following disadvantages:

- Zeros and ones can only define those product properties that can also be represented with modelling software. For example, if the software doesn't know the product characteristic "material", then this characteristic cannot be defined through the building blocks zero and one.
- The description of a product through the arrangement of zeros and ones is very impractical for the product developer, as it is extremely difficult to see the properties of the product from these sequences.

The approach of a binary solution space provides maximal freedom (in the context of a specific software), but is not manageable for a typical user without the conversion via a software system. A possible application is the use of computer supported optimisation methods, which doesn't have problems with high levels of abstraction. Furthermore, it should be noted that such a solution space description will produce very many invalid solutions, if no rules are defined describing when certain combinations of zeros and ones are either allowed or forbidden.

3.3 Prohibition Model

All investigated product development methods use a solution space description with a particularly structured dataset. This dataset contains the solution elements for the emerging solutions. The product developer is thus always offered a limited amount of possible elements. This limitation is based on a specific time point. Based on the whole development process, however, the dataset can be offered dynamically, for all intents and purposes. The more limited the quantity and possible configurations and combinations, the lower the achievable solution diversity and quality. To improve this solution diversity and quality, it is necessary to not "artificially" limit the quantity of solution elements, but to rather include permissible elements for all concrete tasks. Thus follows, however, the almost unavoidable task of holding on to all permissible solution space elements in the solution space description. As the diversity of existing solution elements (materials, manufacturing methods, operating principles, etc) is immense, a complete solution space description at a reasonable cost is in most cases impossible (potential exceptions are tasks with very specific requirements, which leave only a very small range for possible solutions). Since the optimal configuration and combination of solutions elements are not available under these circumstances, the maximum solution quality can't be achieved.
The following solution space model presents an alternative approach. This approach aims to not limit the product developer, and to permit the maximum possible number of allowable solution elements. This will be achieved through an inverted solution space with prohibited areas. In contrast to the typical solution space, this inverted solution space does not contain the set of permissible elements for a solution, but all of those solution elements of which the use for possible solutions is explicitly forbidden. These elements form prohibited areas ("taboo zones") in a, apart of that, virtually infinite (i.e., limited only by scientific laws) solution space. This inverted solution space is referred to in the following as "Prohibition Space".
The definition of a Prohibition Space is initially subject to the same uncertainties as the definition of the "typical" solution space. In addition, it is almost impossible to define all forbidden solution elements. It follows that the Prohibition Space is incomplete at the beginning as well. The difference with the typical solution space is that the product developer is allowed to use too many elements in an incomplete Prohibition Space (so that the possibilities are not limited), while in an incomplete typical solution space, too few elements are allowed and permissible elements are thus suppressed.

3.4 Approach for the Creation of the Prohibition Space

The definition of the Prohibition Space is based on the requirements taking into consideration the various starting and boundary conditions, constraints, and the environment. These can in turn arise from different sources. According to the Magdeburg approach of Integrated Product Development they are all of equivalent importance and influence [Burchardt 2000] [Vajna and von Specht 2006], and they can result from essential equivalent requirements, for example, desired shapes, functions, handling capabilities, creation and usability, manageability, price/performance ratios, legal situations, product sustainability and other sources.

To create the Prohibition Space, mainly requirements and boundary conditions are considered now, as these seem to have the greatest influence. Through the inversion, the appropriate bans can be formulated and the solution elements that are forbidden can be derived (Figure 3). It is important to pay attention that n:m associations are involved between requirements / boundary conditions and solution elements. For the sake of an overview, it is useful to group forbidden solution elements. For example, possible categories are operating principles, materials, manufacturing methods, geometric parameters, standard parts, tolerances, surface finishes, etc.

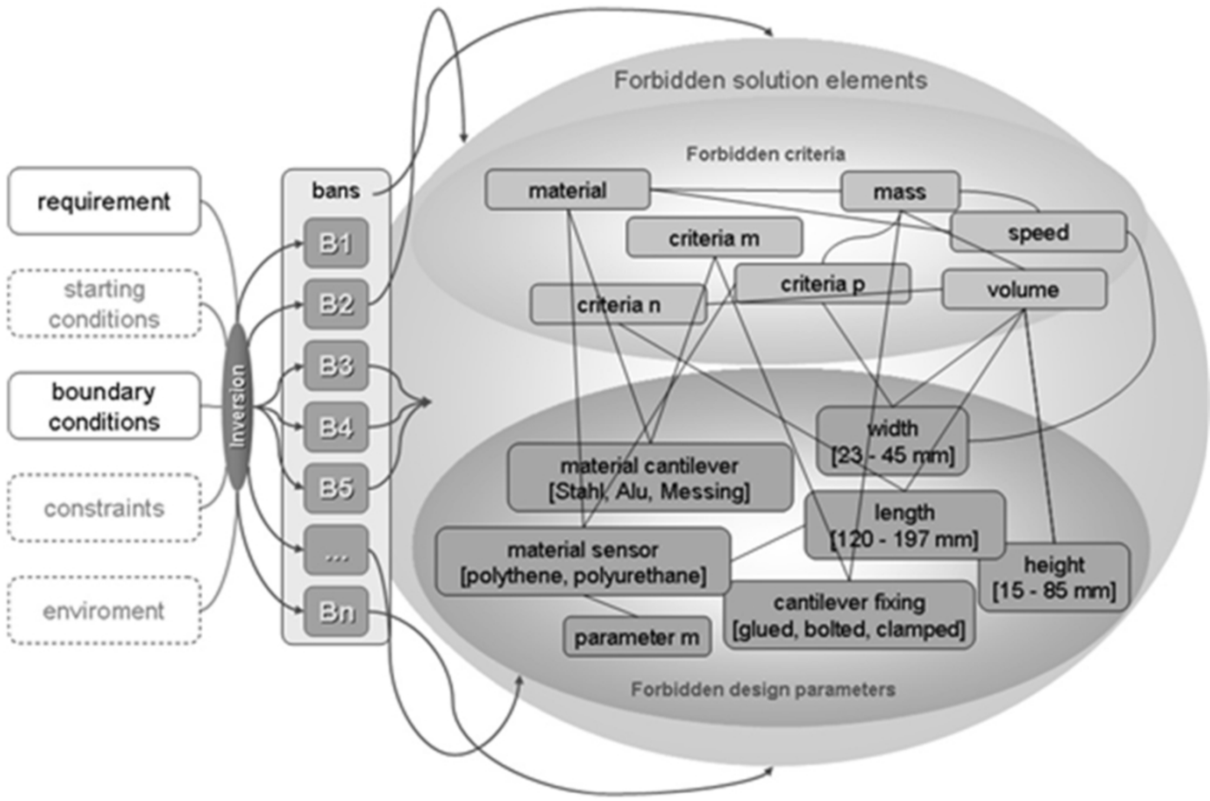

Figure 3. Structure of Forbidden Solution Elements within the Prohibition Space

The creation of a Prohibition Space will be demonstrated in an example (Table 1). The following exemplary requirements exist:

- Non-magnetic
- Safe handling of the operating unit
- 30mm stroke
- Produced in a company with simple manufacturing operations

First, the requirements are inverted. That means if for instance a requirement demands a certain type of energy supply, e.g. electric energy, then the inversed requierement would include all types of energy except electric energy. Then, based on these inverted requirements (= bans), the forbidden solution elements will be determined in the next step. If the requirement is formulated precise, than there is an exact inversion (e.g. magnetic < = > not magnetic). If the requirement is of fuzzy type then the inverted requirement will be of fuzzy type too. In the next step it is tested in which category of solution elements an influence exists. Again, if the inverted requirement is not precise, the forbidden solution elements will be fuzzy too (e.g ergonomical correct operated devices => metal, plastic, glass + slippery surfaces, to small/large diameter). An assignment is not always possible at this point, as for example, the relationships between product criteria and the originating design parameters are not always evident, particularly in the early phases. Unassignable requirements are therefore temporarily not given further consideration. The set of forbidden elements can be further detailed later in the product development process, after knowledge about the influence of design parameters and product criteria is collected. If certain solution elements prove to not fulfil a requirement, this particular solution element will be added to the forbidden solution elements. For example, if it turns out that an operating device made from wood would not ensure a ergonomic correct handling, than the material wood would be added to the forbidden materials.

The difference between a solution space used by existing design methods (the traditional solution space) and the Prohibition Space is presented in Figure 4. The point cloud symbolises all possible solution elements, independent from a specific design task. At the beginning, this solution space is only limited by scientific laws, and is therefore virtually unlimited for "normal" problem solving. While a “traditional” solution space approach (database based) would try to define all allowed points (solution elements), the Prohibition Space approach is going to define areas containing forbidden solution elements (the so-called "taboo zones", represented by the areas within the point cloud.

Another advantage of the Prohibition Space is evident in the early phases of the development process. Due to the lack of knowledge about the relationships between requirements and solution elements, it is often not possible to determine the forbidden criteria, based on the forbidden requirements. The Prohibition Space therefore contains too few taboo zones at the beginning of the product development process. At this time, the product developer is able to use product criteria, for example, that should actually be forbidden. If, for example, impermissible solution elements are used, it will be noticed upon evaluation that the resulting solution possesses impermissible product criteria. This newly obtained information can be used to refine the Prohibition Space.

Table 1. Requirements, Bans and the Resulting Forbidden Solution Elements

Requirements	Bans	Active principle	Materials	Manufacturing process	Ergonomics
Not magnetic	Magnetic Materials		Magnetic materials		
Ergonomic handling of a operating device	Operating devices that can't be operated ergonomical correct		Metall, plastic, glass		Slippery surfaces, too small / large handle diameter
Adjusting stroke min. 30 mm	Adjusting stroke max. 30 mm Complex	Piezoelectric			
Company with simple manufacturing possibilities	manufacturing processes		Composite materials, high tensile steels	Sintering, heat treatment, electroplating, drop forging etc.	

A traditional solution space would in the same case be incomplete as well (due to the lack of knowledge about the coherences). Here, however, "incomplete" means that permissible elements are missing, thereby restricting the product developer’s solution possibilities. Since a traditional solution space consists by definition of only permissible solution elements, only solutions with permissible criteria will be generated (exceptions could be certain combinations of permissible elements). So, an incomplete solution space can’t be noticed at all even if the provided solution elements by far don't represent all possible solution elements.

4. Conclusion and Outlook

The research on designing the solution space for the ADT has shown that the approach of describing a solution space in a form of a "closed volume", i.e. by a complete and consistent description of every boundary component, can't always be realised, thus leading to solutions that stay below their theoretical solution quality. The approach of a Prohibition Space with taboo zones leads, as first tests have already shown, to much more flexible and lucrative results.

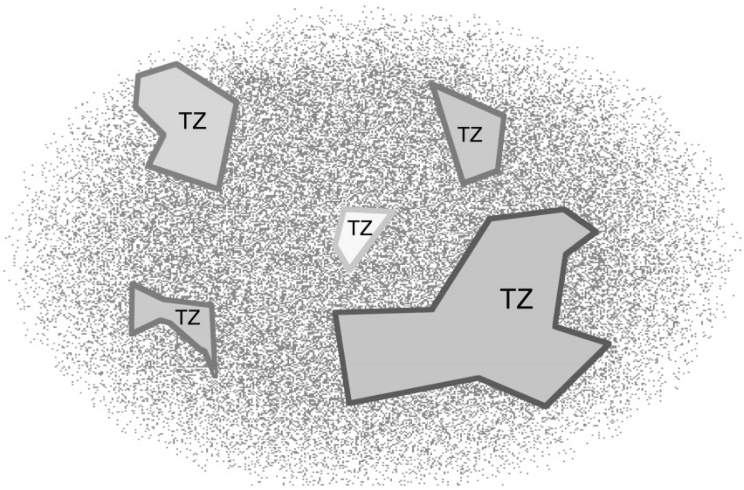

Figure 4. Prohibition Space with Taboo Zones (TZ: Taboo zones)

Generally it can be noticed that both complexity and disciplinarity of products increase towards incorporating domains beyond mechanical engineering. Typical representatives of such multidisciplinary products are mechatronical products, because they don't consist only of mechanical components, but increasingly also of components from electrical enginering, information technology, hydraulics, and pneumatics. Consequently, future research work on the ADT solution space will deal with incorporating and supporting such requirements and conditions that result from the development of mechatronical products. Therefore, the existing approaches, methods and models within ADT will be toughend up in order to handle these kind of multidisciplinary products and the significantly increased amount of data resulting from this multidisciplinarity. Thereby it has to be ensured that the ADT remains generally applicable.

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References

Altshuller, G., "40 Principles – TRIZ Keys to Technical Innovation" (translated and edited by L. Shulyak, S. Rodman). Technical Innovation Center Worcester MA (USA) 2003.

Bercsey, T., Vajna, S., "Autogenetischer Ansatz für die Konstruktionstheorie. Beitrag zur vollständigen Beschreibung des Konstruktionsprozesses", CAD-CAM Report 13(1994)2, pp. 66-71,and 13(1994)3, pp. 98-105.

Briggs, J., Peat, F. D.: Die Entdeckung des Chaos. Carl Hanser Verlag München 1990.

Burchardt, C., "Ein erweitertes Konzept für die Integrierte Produktentwicklung", Dissertation Univesität Magdeburg 2000.

Chen, K.Z., Feng, X.A., "A Framework of the Genetic-Engineering-Based Design Theory and Methodology for Product Innovation", in: Norell, M. (editor): Proceedings of the 14th International Conference on Engineering Design ICED03, presentation 1745, Design Society 31, Stockholm 2003, Abstract p. 671.

Dünser, T., "Unterstützung der Zielorientierung und –formulierung in der Entwicklung komplexer Produkte – am Beispiel einer neuen Aufzugstechnologie", Dissertation ETH Zürich 2004.

Ehrlenspiel, K.: Integrierte Produktentwicklung (dritte aktualisierte Auflage). Carl Hanser Verlag München 2007.

Fan, Z., Andreasen, M.M., Wang, J., Goodman, E., Hein, L., "Towards an evolvable chromosome model for interactive computer design support". In Samuel, A (editor), Proceedings of the 15th International Conference on Engineering Design, Paper 357.46. Melbourne 2005.

Kittel, K., Vajna, S., "Development of an Evolutionary Design Method", in: Leifer, L., Skogstad, Ph., "Proceedings of ICED 09", Volume 6, Design Methods and Tools, Part 2, pp. 147 – 156.

Miller, G.A., Galanter, E., Pribram, K.H.: Strategien des Handelns. Pläne und Strukturen des Verhaltens (2. Auflage). Klett-Cotta Stuttgart 1991.

Vajna, S., Clement, St., Jordan, A., Bercsey, T., "The Autogenetic Design Theory: an evolutionary view of the design process", Journal of Engineering Design 16(2005)4. pp. 423 – 440.

Vajna, S., von Specht, E.-U., "Integrated Product Development as a Design Philosophy in University Teaching", In: Proceedings of IDETC/DED 2006 (ASME), presentation DETC 2006-99091.

Weber, C., "CPM/PDD – An Extended Theoretical Approach to Modelling Products and Product Development Processes". In: Bley, H.; Jansen, H.; Krause, F.-L.; Shpitalni, M. (Editor), Proceedings of the 2nd German-Israeli Symposium, pp. 159-179. Fraunhofer-IRB-Verlag, Stuttgart, 200.

Wegner, B., "Autogenetische Konstruktionstheorie – ein Beitrag für eine erweiterte Konstruktionstheorie auf der Basis Evolutionärer Algorithmen", Dissertation Universität Magdeburg 1999.

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