8th International Conference on Mass Customization and Personalization – Community of Europe (MCP-CE 2018)

Digital Customer Experience
September 19-21, 2018, Novi Sad, Serbia

COMPLEXITY MANAGEMENT OF SOLUTION SPACES IN MASS CUSTOMIZATION

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Abstract: *In today's management literature the term complexity is an often used expression in coherence with offerings on globalized markets and heterogeneous customer requirements. Nonetheless, in a more operational context, complexity management is broken down strictly to the management of product variety. In the present article, the authors take a wider perspective of system theory and cybernetics in order to discuss complexity as ability to mediate between market, offering and value network. Following Ulrich's recommendations for applied research in industrial management, our aim is to connect complexity management to solution space management and synthetize behavioral rules for companies regarding complexity management. After a brief introduction in complex system theory and complexity management, solution spaces are discussed with regard to two complexity dimensions, namely variety and uncertainty. The classical view of a solution space as set of all theoretically feasible solutions for defined sets is then extended. As a result and main contribution of this paper, a solution space-based holistic complexity management approach is proposed.*

Key Words: ***Complexity Management, Solution Space Development, Variety and Uncertainty, Hannover House of Complexity***

1. INTRODUCTION

Manufacturing companies in various industries differentiate their offerings according to a wide range of customer needs [1]. Especially in highly saturated consumer markets, the customer wants to participate in the design process of his individual product in order to realize his personal ideas. Clothing industry, consumer electronics and the automotive industry are frequently discussed and well-documented examples [2]. But also in the business-to-business context, the constant demand for improved performance, better efficiency and higher sustainability leads to cooperative business models and an increased variety [3-5].

There are multiple reasons of increasing product variety. From a social science point of view, due to the high standard of living in the western industrial nations, a strong trend of individualisation is recorded which is even reinforced through increased mobility and a shift in traditional values towards e.g. sustainability [2, 6]. From a marketing point of view, if products are totally comparable regarding characteristics and performance, logistics and the offering of accompanying services like maintanance contracts or financing offers that are sold in addition to the product achieve the necessary differentiation and value perception, e.g. through individualization [5, 7-10]. Additionally, if a company acts on several regional markets, the heterogeneity of requirements grows, e.g. due to different legislation, environmental standards or different cultural influences (sense of aesthetics, etc.). Last but not least, from a production technology point of view, developments in high speed cutting and in additive manufacturing result in incresingly economical production processes that are enablers for lot size one [11, 12].

1.1. Motivation

In order to be long-term successful, a company has to manage the aforementioned concerns permanently, as well as mediate between company, value networks and customers [1, 13-15]. However, if the product variety and the value network are too large, there will be a loss of transparency and high vulnerability to disturbances [16, 17]. This so-called high complexity is expressed, amongst others, by in the following issues:

- Sales of a single product variant, vendor parts, etc. can no longer be predicted with certainty. To guarantee short delivery times, suppliers build up higher safety stocks [8, 18].
- Especially in the capital goods business, customers often may order spare parts for decades after purchase. If master data is not purged regularly, numerous dependencies between projects and product components are established. The effort for configuration management and change management increases [19-21].
- In general, coordination efforts increase at all levels of the value network since the different variants have to be routed through production.

Already small disturbances can take a major impact on schedules and delivery time [16].

- Traditional cost accounting systems lose their applicability, due to cannibalization effects and cross-subsidization [22, 23].

These issues and the resulting so called high complexity are subject of holistic complexity management approaches which try to dampen the effects of product variety [21, 23]. Key tool with regard to product development and operations management is modularity so that new designs are the result of an aggregation of existing building blocks, linked via standardized interfaces [20, 24, 25]. However, these approaches fail in operationalizing complexity so that it cannot be distinguished between good and harmful complexity [17]. Moreover, especially in the German literature, complexity is commonly understood as generally harmful (refer e.g. to [23, 26]).

But there is a business model pattern that manages to combine a high degree of product variety and customization with the production efficiency of mass production. Mass Customization (MC) is a hybrid competitive strategy that combines cost leadership and differentiation with respect to defined markets or single customers [27]. Companies that implement MC and integrate customers into a co-design process create highly specialized, tailored solutions, achieving sustainable and lasting customer loyalty [28]. The core of the concept is a stable solution space from which the individual products, services or solutions may be configured [29]. This is realized by incorporating modern information technologies. Here product configuration systems play a double central role: First, sales configurators allow direct communication between customers and company so that requirements are translated directly into a technical specification [30]. Second, technical configurators in the sense of knowledge-based engineering systems are tools for setting up and exploring the solution spaces themselves [4, 31].

In the present article, the authors want to bring together complexity and solution space management in order to form a holistic complexity management approach that is capable of explaining the success of MC in this area. Therefore, we take a wider perspective of system theory and cybernetics in order to discuss complexity as the aforementioned ability to mediate between market, offering and value network.

1.2. Methodology and Structure of the Paper

Following Ulrich's recommendations for applied research in industrial management [32], a seven step research design was chosen. First, the motivation of the research question and its relevance for practitioners has to be clarifier (sub-section 1.1). Afterwards, relevant theories and hypotheses have to be collected and related to formal methods and models. In this context, the following Section 2 gives an overview about complexity and complexity management. In the next step, the context of application for the new derived theory has to be identified which is done in Section 3 where solution spaces and their management in mass customization business models is discussed. The derivation of management models, behavioral rules and assessment criteria as fifth step of Ulrich's method is mirrored in Section 4 which introduces the approach of an integrated complexity and solution space management by a cybernetic model. Steps 6 and 7 are the test of the new models etc. and the synthesis of management guidelines, which is partly discussed in Section 4 as well. Section five briefly concludes the paper and presents further research needs.

2. COMPLEXITY MANAGEMENT

The scientific discource regarding the term complexity is based on systems theory and cybernetics that aims on control and regulation of dynamic socio-economic, organizational, biological or technical systems [33, 34]. As depicted in fig. 1, cybernetics is able to classify four fundamental system types by the variables variety and dynamics or uncertainty respectively [35].

Simple systems consist only of few elements which interact in a simple manner. The system can act in a limited number of ways which can be analyzed and predicted analytically [33]. A relationally complicit system is built of many elements and relations among them. Its behaviour is generally deterministic and can be analytically modelled with the corresponding effort. Moreover, stochastic approaches allow to simulate and optimize such systems [35]. This is different in dynamically complicit systems. Allthough their set-up is shaped by only few elements, each element is highly dynamic and fluctuating over time so that the system behaviour can hardly be predicted since it may follow too many different trajectories [16]. In complex systems, a high amount of changing elements and many possible behaviours with changing effects come together. Although a complex system may follow very simple behaviorial rules like in the case of a starling swarm, the number of variables and constriants prevents a complex system from being totally predictable. This effect is even reinforced since complex systems are usually not closed and interact with their environment [35].

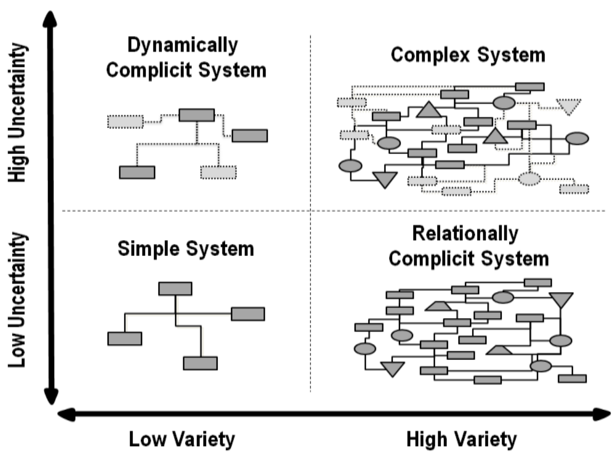

Fig. 1. *Fundamental System Types* (adapted acc. to [35])

2.1. Complexity

Complexity thus represents a system property that depends both on the number of system elements and their relationships as well as on the dynamics of the possible resulting system states [36]. In literature, dynamics are often equated with type and number of possibilities for changing the overall system, system elements and their relationships [37]. At last, this represents just another facet of variety. For this reason, the authors follow Frizelle's [16] argumentation, and regard the uncertainty resulting from dynamics as the second dimension of complexity. This also embraces the emergence as a property of complex systems, which states that individual properties of the system cannot be obviously deduced from the properties and behavioral patterns of its elements [35].

With regard to manufacturing companies, literature distinguishes between external and internal complexity [20]. External complexity results from the number, heterogeneity, and weighting of customer requirements and determines the variety of products offered by the company [37]. Internal complexity is described as the number of subassemblies and parts, as well as the laws-of-creation that describe how these are assembled to end products. This is supplemented by the arrangement and size of the value network [31].

2.2. Complexity Management

Generally, two different research streams for complexity management can be found in literature. First, there are numerous approaches that are specific to individual organizational units of a company (e.g. production) or single methods for complexity management, such as variant costing or product structuring (e.g. refer to [8, 16, 20]). With respect to the corresponding research question, such approaches may contribute to a better understanding of complexity in the particular case. But as was derived form systems theory above, it is at least questionable if these approaches, which target on only sub-systems within an organization, can help companies to find the global system optimum regarding complexity. As introduced above, emergence means that the global optimum is not necessarily the sum of all optima in all sub-systems.

The second research stream deals with holistic, integrated complexity management approaches that are based on the analysis and understanding of complexity drivers and their impact on organizations [21, 23, 26, 37]. A definition was e.g. provided by Schuh who understands the management of complexity as "*the design, development and control of business activities regarding products, processes and resources. By managing complexity it is aimed at dominating diversity along the whole value chain so that customer satisfaction as well as organizational efficiency gets maximal*" [37]. The starting point in most approaches is the reduction of product and process variants [22]. In the following, two very different examples are presented which target on different complexity dimensions.

In his work, Wildemann [23] addresses the connections between drivers of complexity, methodological support and tools for complexity management. Basis for this is the evaluation of best practices and the collection of examples of the practical application of complexity management which is broken down into individual organizational units.

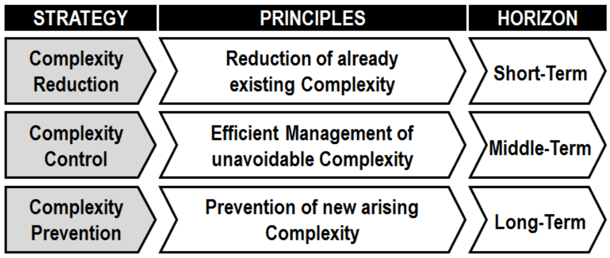

Fig. 2. *Phase Model of integrated Complexity Management acc. to* [23]

The core of the concept is a phase model (fig. 2), which consists of the three steps of complexity reduction, complexity control and complexity prevention. The first step is to consistently streamline current product and process characteristics and thus realize a short-term reduction of complexity. In detail, unprofitable product variants have to be phased out or immediately deleted. As well, the diversity of semi-finished products and raw materials has to be reduced. The second step is designed for a medium-term period and includes measures to develop complexity consciously and purposefully. Here, Wildemann formulates e.g. the demand for an optimized production organization and order processing as well as for product development methodologies that are appropriate for variant design. Measures of complexity prevention can usefully be applied in product and process development in the last step, so that a detrimental amount of complexity does not arise at all. This mainly includes cost / benefit calculations of new variants to be developed. As can be seen, Wildemann aims at a total reduction of complexity and concentrates on the dimension "*variety*".

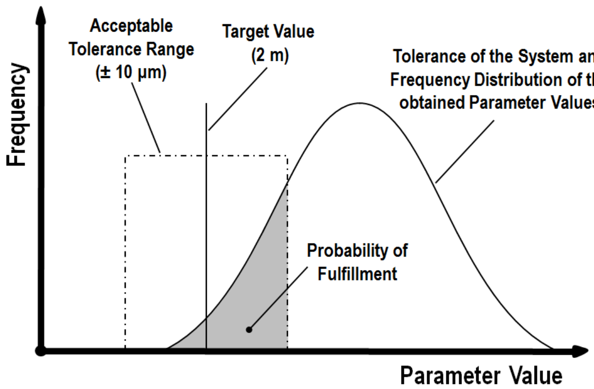

Fig. 3. *Complexity Management in Axiomatic Design (acc. to* [38]*)*

As part of his design method *axiomatic design*, Suh [38] defines complexity not in the physical domain (products, services, organizational units) but on a functional level. For him, complexity arises from the uncertainty of translating requirements into functions and ensuring that these requirements are met. The concept can be illustrated by a production system for rods: The rod should have a finished length of 2 m, the tolerance is ± 10 μm (functional requirements of the manufacturing system). If the tolerances of the manufacturing system are included in the consideration, a probability distribution is created in which the length of the rod will lie (fig. 3). If it can now be ensured that the tolerance of the rod is always within the probability distribution of the system, the complexity is zero - if it is completely outside it is infinite. In the example of the rod production, these relationships can be described analytically. In the case of multipart products with complicated manufacturing and assembly sequences, however, dependencies and conflicts arise between the individual functional requirements. In addition, the tolerances and probability distributions of the mechanisms with which a requirement is to be met are usually dynamic and depend themselves on a variety of factors. Modeling within axiomatic design helps to identify and simplify such dependencies. As can be seen here, Suh aims at a neutral definition and description of complexity and on its reduction, but integrates solely the *uncertainty* dimension of complexity.

A detailed description and analysis of existing holistic complexity management approaches would be beyond of the scope of this article. Nevertheless, a review of the existing approaches referred in [23, 26, 37-39] showed the following issues:

- Most approaches aim at reducing complexity, possible positive effects are nearly completely negated or overseen.
- Many of them are implemented as phase model which is often criticized in literature. A phase model in this context often leads to an occasional reduction of variety, uncertainty and resulting complexity, but does not allow shaping a fundamental strategy or long-term optimization.
- Commonly, there is a lack of a reference framework like business typology or solution space so that even documented examples or best practices hardly can be mapped on another entrepreneurial context.
- Only single approaches integrate uncertainty as complexity dimension. In most cases complexity management is reduced to variety management which is indeed not the same.

3. SOLUTION SPACE MANAGEMENT

In order to formulate a complexity management approach that is related to solution spaces and includes both complexity dimensions, this section is dedicated to the design solution space itself. After a general discussion of different solution space understandings, a relation to MC business models is drawn.

3.1. Design Solution Spaces

Literature reports about four different views of design solution spaces, which all can be integrated in a joint understanding.

First, a solution space can be understood as set of all existing product variants that either fulfill specific functions or defined requirements (refer e.g. to [40, 41]). Ponn expands the term in relation to a given design task and introduces the requirement space as a set of all development goals and required product characteristics [40]. In the product development process, the required product properties are compared with the properties of the designed artifact and approximated by synthesis analysis loops (fig. 4). It has to be stated, that usually not all areas of the solution space are accessible due to restrictions from manufacturing, legislation, etc. [42].

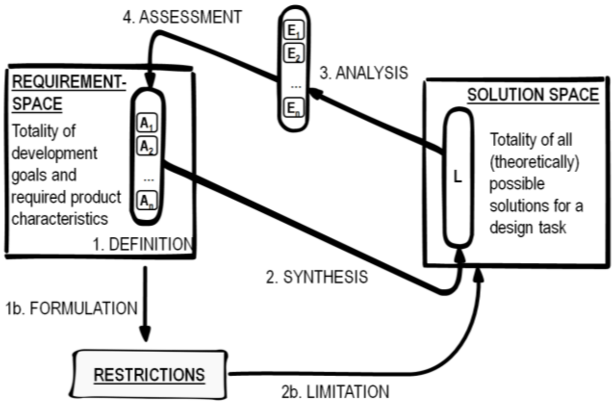

Fig. 4. *Requirement space and solution space in the development process* (adapted acc. to [40])

Most approaches that cover this **external variety view** (according to external complexity, see above) on a solution space include interactions and connections between solution space and requirement space, but only on conceptual levels or with reference to requirement engineering.

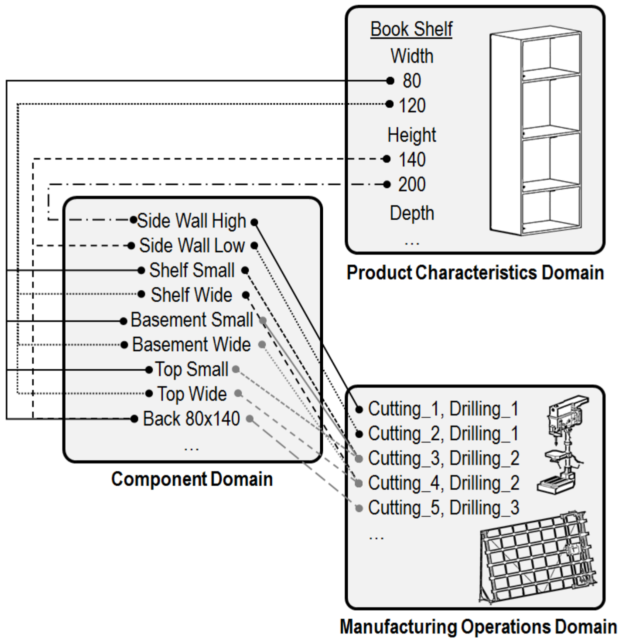

Fig. 5. *Combined Product and Process Configuration acc. to* [43]

Second, the solution space may be understood as the set of all existing product components and the laws-of-creation, how these are connected to the final product (refer e.g. to [38, 43]). Usually, methodologies that use this **internal variety view** on the solution space are set up on a domain concept like proposed by Aldanondo [43]. The first domain contains selectable product features and their characteristics which are mapped to product components or features in the second, the design domain. The third domain contains the manufacturing processes used to produce and assemble the individual product variants (fig. 5). In turn, properties, components and process chains are formulated as a constraint network. Since resources such as production equipment and processing time can be assigned to a process chain, Aldanondo is able to formulate joint product and production process configuration based upon customer requirements.

Third, the solution space is seen as search space within a development project. As the development process progresses, this search space converges until the desired artefact is found (refer e.g. to [44, 45]). As a consequence, most approaches that cover this **exploration view** of the solution space provide tools for concept evaluation or decision making.

Finally fourth, which in turn reverses the aforementioned, is the **degree-of-freedom view**. Here, the solution space as a variation space of a known design (refer e.g. to [46, 47]). An often cited concept is Gero's design prototypes which represent spaces where a design artefact, regardless whether product, subassembly or single part, may be altered in a certain way (fig. 6). This ranges from simple parameter changes to the traditional approaches to variant and adaptive design.

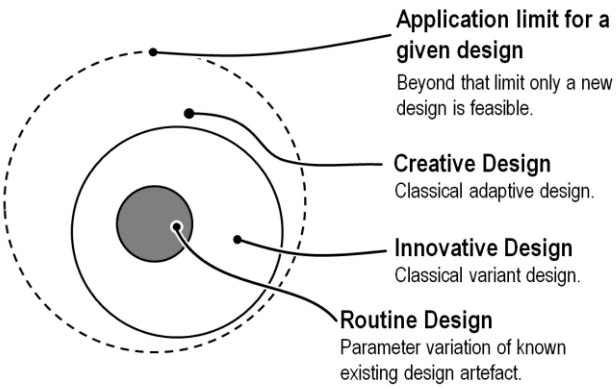

Fig. 6. *Design Prototypes* (acc. to [46])

3.2. Solution Spaces for MC Business Models

As key principle of MC in order to overcome the apparent contradiction between individual products and mass production, it is necessary to carry out the co-design process within a defined, stable solution space, as stated above. According to the business model and the offering, six different co-design activities can be distinguished that lead to different content in the solution space [5]. Regarding the design of physical artefacts that can be manufactured and where integrated complexity management can show its full potential, two co-design activities are of mayor interest.

Composition customization is a very prominent and often used concept since it addresses the aggregation of totally predefined building blocks. These are assembled via standardized interfaces, so that a modular design concept is present which is then usually produced in an assemble-to-.order strategy [42]. As a consequence, design, production and testing of each of these modules can be done independently from the whole system. The laws-of-creation can be formulated as constraint networks or rule-bases which are easy to understand [5]. Additionally, composition is widely used, when physical and intangible parts, like services, of an offering have to be configured jointly [10]. The external variety view of the solution space thus contains all possible and valid compositions of building blocks, whereas the inner variety view contains the building blocks themselves and the combination rules or interdictions.

In aesthetic co-design, this is different. Here, the customer is allowed to adapt the outer appearance of his product also in sense of shape. So he is able to change e.g. a casing or fancy covers. This is challenging in two directions: On the one hand, the design has to be validated so that there is no impairment of the final product (e. g. because a housing has been modeled too small and collides with other components or a design interface between housing and module carrier has been changed so that final assembly is no longer possible). So the solution space must contain such restrictions in the internal variety view. On the other hand, particular manufacturing processes are needed such as additive manufacturing or high speed cutting in order to realize efficient production also in case of lot size one. The corresponding manufacturing restrictions, like the size of the process chamber in selective laser sintering, have to be formulated as well [12].

4. COMPLEXITY MANAGEMENT OF SOLUTION SPACES

When a configurable product is designed, the complexity is partly reflected by the solution space from which the individual variant is derived. Both variety and uncertainty can be used for the description of the solution space [48]:

- Size of the possible solution space: This refers mainly to the external variety view and answers the question how many product variants / possible solutions are described in the solution space. Main focus is on the variety dimension of complexity.
- Connectivity of multiple solution spaces: The connectivity is a result of the internal variety view and reflects how many solution spaces interact with each other and of which kind this interaction is. Main focus here is on the variety dimension of complexity, too.
- Degree-of-Exploration: This corresponds to the exploration view. The question is if all product variants are predefined or pre-calculated beforehand or if there are any unknown areas of the solution space. Focus thus shifts to uncertainty.
- Closure of the possible solution space: Here, the degree-of-freedom view comes into play. Main problem is if all limitations, either technical like manufacturing restrictions, design interfaces or economic ones such as minimum lot sizes, etc., are known and formulated explicitly. Here, the focus is also on uncertainty.

If now complexity has to be developed purposefully, the solutions space has to be developed purposefully as well. This is indeed challenging since the solution space is not an isolated system of products but has strong interactions to requirement space and value chain configuration space that describes the portfolio of capabilities of the entire value network (fig. 7).

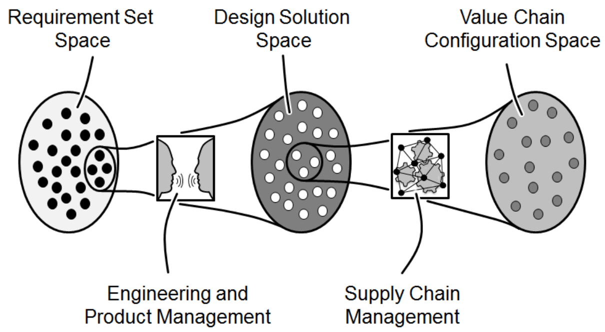

Fig. 7. *Relation of Requirement Set Space, Design Solution Space and Value Chain Configuration Space [48]*

Based upon this, the authors developed the following complexity management approach based on design solution spaces.

4.1. Theoretical Model

In the authors' understanding, variety and uncertainty of a solution space generally call for two different management activities. On the one hand, variant management targets on the variety dimension of complexity. The authors basically follow the argumentation of Rathnow [49] and Schuh [37]:

Variant management is the development, design and structuring of the offer (products and / or services) or assortments within the company. The aim is to develop the external and internal variety resulting from the offer by means of suitable tools in accordance with the competitive strategy.

Targeting on the uncertainty dimension, the authors developed the following understanding:

Complexity management is the design, control and development of degrees of freedom and uncertainties in relation to the business activities of a company. This results in the ability to constantly mediate between the market, offering and value network in order to create maximum customer benefit and high profitability through robust processes for development, production and distribution.

In contrast to earlier definitions this one is less abstract since it clearly addresses the degrees-of-freedom of requirements, offering and production processes. Based upon this, the authors developed a joint cybernetic approach for the solution space-based complexity management which is shown in fig. 8.

Core hypothesis is that a demand for complexity that arises from different customer needs and requirements and a potential for complexity resulting of the portfolio of capabilities have to be balanced. A mismatch between both has to be regulated: Either through complexity reduction, if the portfolio of capabilities is too big and thus ineffective or expensive (e.g. because process variants have to be maintained that are rarely used). Or through increase of complexity because customer needs cannot be met.

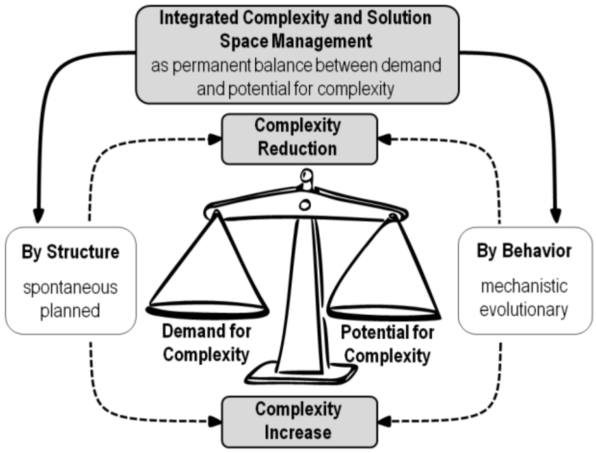

Fig. 8. *Integrated Complexity and Solution Space Management*

These two basic control mechanisms can be addressed by the two actuators structure and behavior. To explain the functioning more clearly, the integrated complexity and solution space management is further discussed on an example case.

4.2. Application

A company for kitchenware detects a demand for individualized toasters. In order to satisfy this, the manufacturer decides to broaden the existing assortment of three basic shapes and allow customers to individualize the housing of the toaster. An increase of complexity is necessary which is primarily initiated by the actuator *structure*. In order to increase the number of toaster variants, the manufacturer *plans* a modular design of the housing that now consists of four parts, each in seven different colors, plus machine elements (buttons, screws, etc.), as depicted in fig. 9. The business model is thus shifted to composition customization.

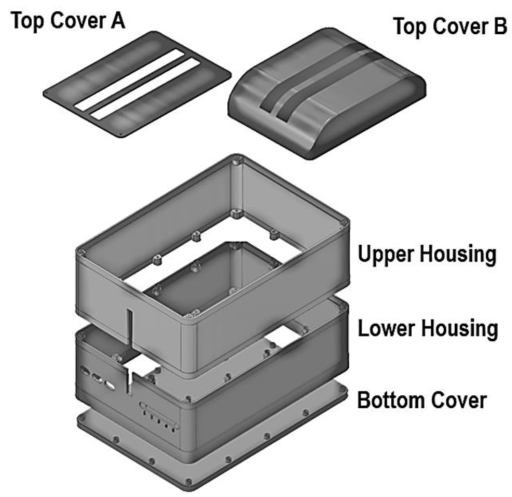

Fig. 9. *Modular Toaster Housing*

In a first distribution step, key customers are invited to configure their individual toasters. This reveals that certain color combinations are favored which are formulated as style templates for the later roll out of the configurator for the entire market. Moreover, the key customers articulated their wish to have two additional colors in the offering. Both issues express *spontaneous structures* that occurred and influenced demand and potential for complexity. In case of the templates, these structures even reduce complexity for single users: A concept that is discussed together with MC is mass confusion [50] that occurs when a customer gets too many choices. Taking a template as a starting point, this is obviated [51].

In order to allow even a higher amount of customization, the manufacturer decides to change the business model to aesthetic co-design. Therefore, the configurator is extended so that the shape of the lower and upper housing parts can be adjusted by the customer. The manufacturer thus changes his behavior: He gives up control to other players in the supply chain and thus introduces uncertainties since the shape as result of an individual taste hardly can be predicted. This is understood as *evolutionary behavior*. In order to process the different parts, a laser sintering machine is purchased and again a test with key customers is launched. This test reveals that process stability is of bad quality since the configured housing parts have failures and collisions to other parts. In other words, there are too many degrees-of-freedom, constraints are not known and value ranges are not validated. This can be overcome by *mechanistic behavior* so that the degrees-of-freedom are partly eliminated and formulated restrictions like process chamber, design interfaces and specific design guidelines for laser sintering are implemented into the corresponding configuration systems.

4.3. Discussion

To be fully operational, the cybernetic model lacks of control variables and metrics which is currently under development. The four dimensions of the solution space are the starting point, e.g. the connectivity of multiple solution spaces may be expressed through width and depth of the structure or variant bill-of-material of a product or product family. The size might be expressed as number of possible end product variants that have been validated. Nevertheless, discrete values might be difficult to formulate. E.g. what size of the solution space is advisable? If 100 variants is acceptable, is this also true for 120 and where is the limit where a product system collapses? What influencing factors can be found for this?

So it is obvious that the uncertainty dimension might be a better starting point. If, in accordance to Suh, uncertainty can be reduced to zero since all restrictions, constraints and solutions are known or can be somehow calculated by the design system then complexity is reduced to a minimum.

Coming back to the four main deficiencies that were formulated at the end of section 2, the proposed approach is able to address the following issues: (1) Both a complexity reduction and a complexity increase are possible to introduce; (2) it is implemented as cybernetic model and control circuit; (3) the solution space was chosen as reference framework; and (4) uncertainty is implemented as dimension of complexity.

5. CONCLUSION AND FURTHER RESEARCH

In the present paper, an approach for integrated complexity and solution space management was proposed that encompasses the two complexity dimensions of variety and uncertainty. The approach is formulated as cybernetic model that addresses control mechanisms for complexity reduction and increase, using the actuators structure and behavior.

Further research may aim at the implementation of a formal complexity management process parallel to configuration management or quality management. Precondition for this is the implementation of metrics. Additionally, it would be interesting to analyze and different competitive strategies in order to synthesize best practices and a toolset that is transferable to other use cases within comparable business models. With the Hannover House of Complexity [31] a corresponding framework was already proposed to classify different methods, tools, etc. with regard to their effect on the single complexity measures and to document the interactions between such methods and tools. Main point of interest is design wizards and knowledge based engineering systems. Both are tools for modeling of solution spaces themselves.

The interesting point is the modeling effort. In the case of the toaster restrictions and constraints can easily be implemented in such a system. Describing the solution space for a whole car, in contrast, is challenging and results in a constraint net that cannot be computed. Moreover, the more constraints are implemented the higher is the risk for conflicting ones.

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