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IMPACT OF RULE-BASED SYSTEMS ON PRODUCT COMPLEXITY

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Abstract: *Mastering complexity in product development is focus of knowledge-based-engineering (KBE). Rule-based systems for product configuration, like used in mass customization business contexts, and design synthesis belong to the oldest but still used implementations of KBE-methods. In the present article, the impact of rule-based systems on complexity is discussed. Therefore, different complexity measures are developed and visualized in the Hannover House of Complexity which has to be understood as framework for company specific complexity management. It focusses on size, degree of exploration and uncertainty of the design solution space, interaction of multiple solution spaces and the uncertainty of the overall system behavior. Afterwards, rule-based systems are characterized and assessed.*

Key Words: ***Product Complexity, Product Variety, Hannover House of Complexity, Rule-Based Systems, Knowledge-Based-Engineering,***

1. INTRODUCTION

Increasing demands on the technical performance and quality of new or enhanced products lead to shorter product lifecycles and hence shorter development times. On the other hand, the demand of the global market and product customization lead to a frequent adaptation of products to different functional or design requirements and so to larger product variety [1].

The complexity that arises in product development due to the aforementioned issues is tackled by the methods of variant design such as parametric designs, design platforms or modular design kits [2].

In order to explore the defined solution space rapidly and efficiently as well as to ensure a high level of innovativeness, the utilization of existing knowledge and the automation of design tasks are critical success factors, so the organizational efforts for creating product variety are minimized [3].

Commonly, the term complexity is used synonymously for product variety in this context. A generally accepted definition for complexity in engineering design is yet not at hand but most approaches include organizational effects and take into account that high variety leads to problems and uncertainties in forecasting demands and control of manufacturing and operations. Furthermore, complexity is considered to be strongly company specific [4].

Different approaches for complexity management exist which target e.g. on mastering product variety or production complexity. The Hannover House of Complexity is a more general framework where business typology and complexity measures as well as methods and tools for complexity management are joined [5].

In the present article, rule-based systems as one example of knowledge-based (KB) or knowledge-based-engineering (KBE) applications are assessed regarding their impact on product complexity.

1.1. Motivation

Especially in the competitive strategy of mass customization, the resulting need for flexibility in product development and manufacturing calls for adequate information technology support. Solution space development using product configuration systems is considered as one building block to complexity management.

Product configuration in this context belongs to the field of KB and KBE applications. From point of view of computer-aided engineering, KBE extends the abilities of parametric modeling by implementing explicit design knowledge into the virtual product models [6].

Rule-based systems belong to the oldest but still deployed applications of KB/KBE. Used as reasoning mechanism in the early expert systems in the 1980ies and 1990ies they provided sales support as configuration systems and they automated routine tasks in various disciplines of engineering design. Today, many CAD-systems still have the possibilities to use design rules for variant design automation.

Nevertheless, the impact of rule-based systems on product complexity and solution space development is still an open question. In this paper we will bridge this gap and show how such systems affect complexity measures.

1.2. Structure of the Paper

In the following section 2 a brief introduction into the concept of product complexity, its measures and its management is given. Afterwards in section 3 the Hannover House of Complexity is introduced as complexity management framework. Section 4 contains the discussion of rule-based systems. Their assessment regarding the single complexity dimensions is part of section 5. The final section 6 summarizes the paper and draws further research questions.

2. PRODUCT COMPLEXITY

Generally, cybernetics and system theory are origin of complexity theory [7]. Thereof different approaches have been derived and further developed for various scientific disciplines such as e.g. natural science, social and labor science [8]. Nonetheless, general definitions or modeling principles do not exist. Complexity is rather mapped and reduced on the particular problem statement.

Approaches in engineering design are typically broken down to complexity of products as well as development and production processes. Usually, external and internal product complexity is differentiated. The first is understood as diversity of a company's offering (number of product variants), the latter is defined as number of subassemblies and components as well as their design and combination rules in order to assemble them to end products [9].

A lot of authors emphasize that product complexity and process complexity are strongly intertwined. Multi-variant products thus lead to an increase of complexity in all operational structures and processes since the high quantity of end products and their components as well as the corresponding documents for each project and each customer have to be managed in operations and the whole supply chain [10].

2.1. Complexity Measures

The lack of a common definition of complexity is continued in measuring it. If complexity has to be managed it is necessary to determine an ideal amount of complexity or to differentiate between good and bad complexity. The early attempts of finding descriptive dimensions failed and resulted in a multitude of measures which could not exactly assess complexity [4].

For his complexity management approach, Schuh uses the so called complexity drivers which is diversity on the one hand and dynamics on the other hand. His concept of diversity encompasses both the diversity of system elements and the diversity of relations between these elements as well as the variety of system states over time [11].

Gießmann uses a compact approach from point of view of logistics and describes complexity in the dimensions of variety, heterogeneity, diversity and uncertainty. All these dimensions are dependent since e.g. an increase of dynamics results in an increase of uncertainty because the prediction of future developments and system states is more difficult. So, it is not enough to measure a single aspect of complexity or to consider only a limited count of system elements but to examine the whole system and all possible occurrences [12].

Broken down to manufacturing organizations, Frizelle reduces this to even two dimensions by the consideration that complexity arises out of the presence of variety since increasing variety generates uncertainty so that the system's behavior cannot be completely predicted. According to him "variety can be seen in terms of trajectories – the path a system traces over time; the greater the variety, the more trajectories are open to the system. Uncertainty comes from not knowing which trajectory the system will follow" [4].

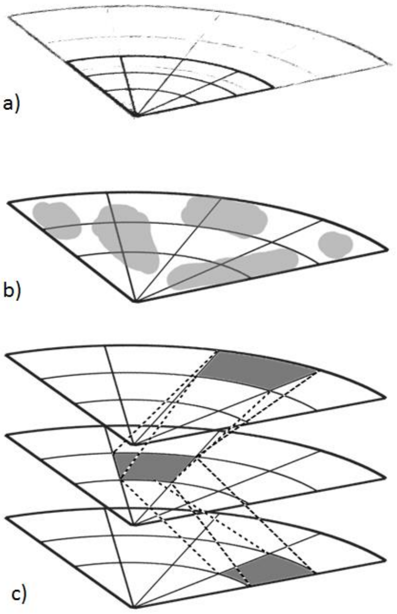


Fig. 1. *Complexity Measures of a Solution Space for Product Development: a) Size and determination of the Solution Space, b) Degree of Exploration of the Solution Space, c) Interaction between multiple Solution Spaces*

When designing products for mass customization, the possible product complexity is reflected by the solution space of which the individual variant is configured from. Here, diversity and uncertainty are both concepts that may be used for assessment of product complexity and lead to five complexity measures (fig. 1):

- Size of the possible solution space: How many product variants / possible solutions are described in the solution space?
- Determination of the possible solution space: Are the limits of the solution space known and predictable? In other words, are all design limitations like manufacturing restrictions, design interfaces, etc. known?
- Degree-of-Exploration: Are all product variants / possible solutions predefined or pre-calculated or are there unknown areas?
- Intersection of multiple solution spaces: How many solution spaces interact with each other?
- Interaction of multiple solution spaces / overall system behavior: Is the relation of all solution spaces to each other clear and describable as well as their design restrictions?

Linked to product development, two observations stand out. First, the degree-of-exploration also marks the potential for conflicting solution elements. Since most product designs for mass customization rely either on parametrization or on aggregation of predefined components, restrictions to value ranges or combinations are usual to obviate unfeasible designs. So, if not all possible end product variants are predetermined, the validity of some variants may not be checked unless all relations between all components are modeled explicitly.

Secondly, commonalities are expressed in intersections and interactions of multiple solution spaces which are important for change management. Intersecting solution spaces mirror parent-child relations on the one hand, since the solution space of the end product is linked to the solution space of the constituting sub-assemblies and so forth. On the other hand they show cross references where a sub assembly is built into different end products. Interacting solution spaces are linked via constraints which correspond to functional or logical relations. The more relations a system has, the more complicated is the prediction of effects when components change.

2.2. Complexity Management

According to Schuh, the management of complexity is “the design, development and control of business activities regarding products, processes and resources. By managing complexity it is aimed to dominate diversity along the whole value chain so that customer satisfaction as well as organizational efficiency gets maximal” [11].

Generally, different aspects of complexity management and single tools can be found in literature. Bliss concludes that the major process management schools of the 1990’s (i.e. lean management, business process reengineering and variant management) may also be regarded as complexity management methods. Especially variant management concentrates efforts on product complexity and customer complexity [13]. Here, e.g. modularization is a valuable building block.

From our point of view, this argumentation leads to three basic views of complexity management [5]:

- Management of product complexity: Measures in different areas of the company, which purpose is designing and controlling the complexity of end products as well as their components and individual parts depending on their functional and design requirements.
- Management of resource complexity: Methods in order to design and control the complexity of production resources, raw materials as well as knowledge and personnel in the value chain.
- Management of process complexity: Approaches which aim at design and control of complexity of operational and organizational structures.

As basic strategies for complexity management literature mentions three basic courses of action. First, existing complexity has to be reduced which aims at streamlining the existing product and process portfolio for a short term effect on product complexity. As result, product variants with low demand and overlaps in the over-all offering are identified and then eliminated.

Secondly, the implementation of complexity control targets at strategic planning and development of the necessary complexity. Here, the methods of variant design like product family design, modular design kits and solution space modeling in general are subsumed. Additionally, an according setup of the manufacturing organization and of order processing has to be implemented.

The last step is prevention of complexity. All new product and process variants have to be assessed regarding additional benefits for company and customer before realization and implementation.

3. HANNOVER HOUSE OF COMPLEXITY

The Hannover House of Complexity has to be understood as framework in which different methods, tools, etc. are classified with regard to their effect on distinct complexity measures. The basic concept of the House of Complexity is depicted in fig. 2. In principle, the design is similar to the House of Quality known from Quality Function Deployment.

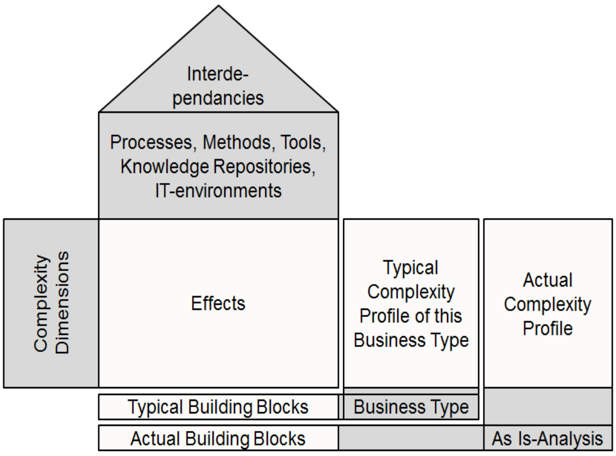


Fig. 2. *The Hannover House of Complexity – Architecture [5]*

In opposite to QFD, the major areas are not the mapping of customer requirements to functions or properties of the product but the mapping of different building blocks for complexity management and their particular effects on different complexity dimensions. In the roof of the House of Complexity the interdependencies between these building blocks are rated to estimate weather two of these building blocks intensify the benefit or extenuate each other. Since the framework is setup as aid for decision making, a reference to a standard company of an according business type is given for comparison. This includes the choice of typical building blocks on the one hand. On the other hand it also allows the assessment of the usual complexity profile at this particular business type. The architecture of the House of Complexity is completed by the fields for the as-is-analysis. An example of the detailed framework is given in fig.3.

In the example, the effect of different building blocks for complexity management on the dimensions of product complexity is shown conceptually. Based on a business typology a company assigns itself to a business type 1. Comparing both complexity profiles shows that in contrast to the benchmark the interaction of solution spaces, the degree of exploration and the over-all

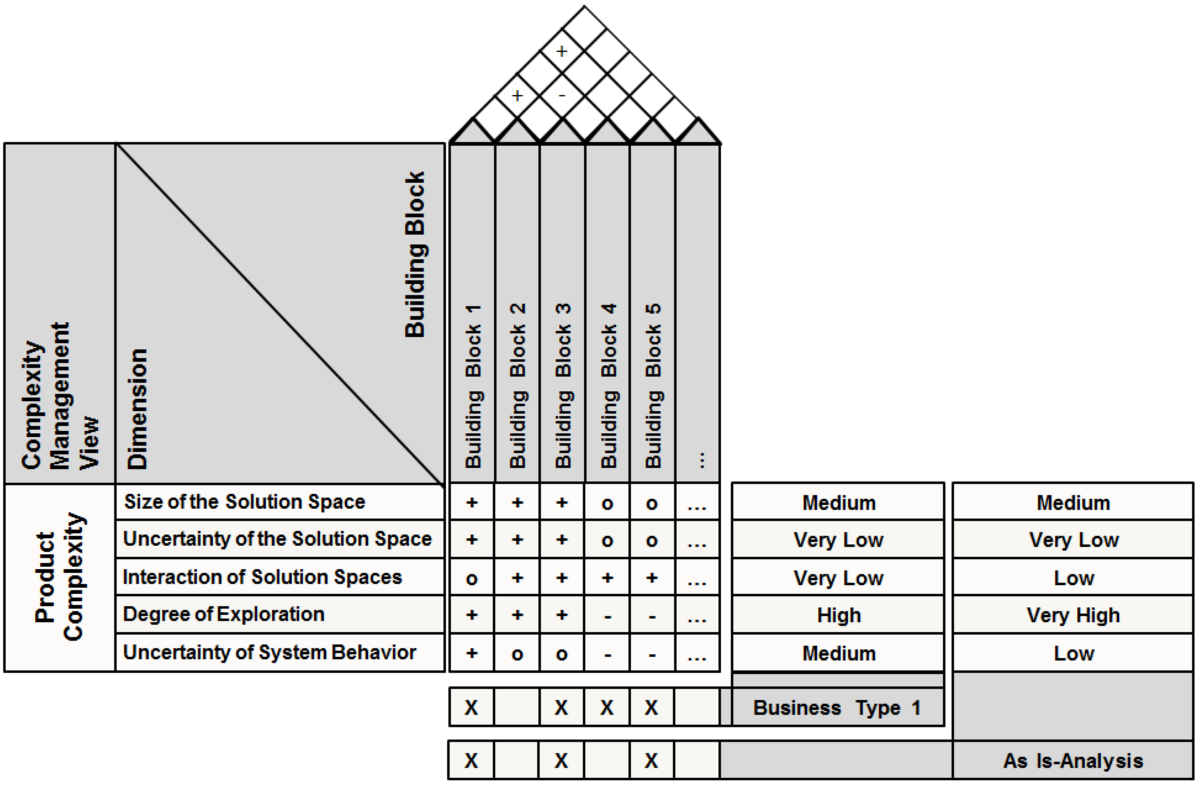


Fig. 3. *The Hannover House of Complexity – Framework [5]*

uncertainty of the system's behavior differ. This is due to the missing of a complexity management building block which is yet not implemented at the company.

Furthermore in the roof the mutual effects of building blocks one to five are depicted. As can be seen from this example it is not the aim of minimizing every complexity dimension. In the example above, the uncertainty of the systems behavior increases.

4. RULE-BASED SYSTEMS

From a wider angle, the early rule-based systems belong to the class of knowledge-based systems which purpose was to replicate human experts for certain problem solving domains. This can generally be divided into two blocks. The first deals with synthesis (e.g. synthetic design, configuration or planning), the second one targets at analysis (e.g. classification, diagnosis or prediction) [14]. In the next sub-section, two examples of expert systems form the 1980ies are presented where R1/XCON represents a system for design synthesis and configuration while MYCIN stands basically for a diagnosis system.

The second sub-section shifts the focus from knowledge-based to knowledge-based-engineering systems. Here, problem-solving is linked directly to computer-aided-design [15].

In both application domains, rules show up as approach for knowledge representation as well as inferencing. Basically, the rule concept is grounded upon the IF-THEN-ELSE-notation known from software development. The tools for creating rule-based systems are easy to learn and simple to use. Nevertheless, different authors point out that such systems become difficult to maintain when they grow very large and reach a certain amount of rules [16].

As stated by Cederfeldt, rules are able to code the following categories of knowledge and problem solving abilities [17]:

- Purely empirical knowledge: Statements of facts and relations derived from experiments. This type of knowledge is usually of explicit kind.
- Rules of thumb / common practice / heuristics: Simplified statements of facts and relations derived from experience. Heuristics are formulated explicitly or implicitly
- Common Sense: Statements about beliefs or habits derived from e.g. tradition or personal perspective. That kind of knowledge is usually implemented as implicit or explicit network of information.
- Logic Reasoning: Ability to conclude effects or actions from rules and facts. In context of KB or KBE this has to be stated based on explicit knowledge.

4.1. Rule-Based Systems in the early Days of KBE

One of the most famous and discussed implementations of a rule-based system is McDermott's R1/XCON configurator. It was designed to configure VAX-11/780 computer systems and proved valuable support for the sales department because the validity of each requested variant was checked immediately based on the customer order. If the configurator identified any incompatibilities it could provide assistance in modifying the design according to the given requirements [18].

Knowledge had to be represented in two different contexts. On the one hand knowledge about the available sub-components of a VAX-11 computer system was hardcoded, i.e. electrical properties, number of interfaces to other sub-components, etc.

On the other hand, rules had to be implemented that allow the formulation of feasible designs. Therefore, knowledge about constraints in the system configuration must be formalized in an explicit way (e.g. if the number of data storages exceeds the controller capacities the configurator must either warn the user or give him advice to choose a controller with more ports), as well as associations of sub-components (if the one is chosen, the depended one has to be chosen as well).

The system was a classic procedural program in which the configuration task was traversed in a sequential way. Nevertheless, not all rules were fired since the system had the ability of deleting unnecessary rules from the working memory or including new sets of rules where needed for decision making. Therefore, so called sequencing rules were used which determine the order in which decisions in the configuration process have to be made so that the resulting end product variant is valid.

Started with over 770 rules and approximately 300 components the system developed over its life time to 17500 rules and over 31000 components. Due to product development, nearly 40 percent of all rules had to be revised yearly.

Another original implementation of a rule-based system is MYCIN which was planned as diagnosis system for infectious diseases. Here, the rule concept was used particularly due to its ability to capture heuristic knowledge (rules of thumb).

In contrast to R1/XCON, MYCIN was designed to explain its reasoning to the user. In that special case, the rule base has to be understood as network of goals (analysis of the patient's state or advice for medical treatment), hypothesis (possible causes for the patient's state) and the constraining rules [19].

Besides the formulation of explicit knowledge in rules, MYCIN shows a crisp separation of domain and control knowledge. The first is called structural knowledge and holds the knowledge about problem features and diagnosis. The latter is called strategic knowledge and is represented by meta-rules that order and restrict rule activation and reasoning.

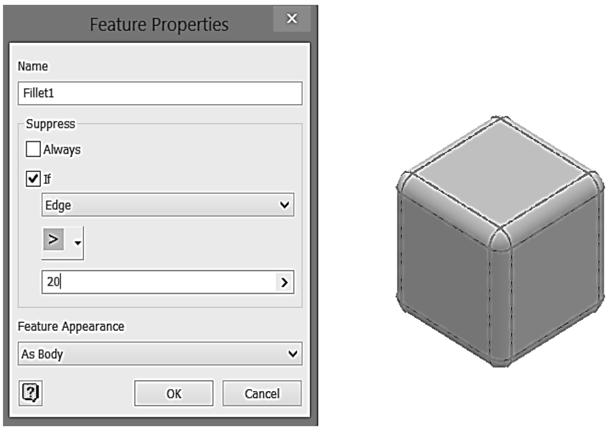
4.2. Rule-Based Systems today

Especially for local and well-structured problem domains the rule concept is still state-of-the-art. Many of today's commercial knowledge-based configuration systems still use the rule concept with stronger or minor focus. An example is web-configuration in automotive development where a lot of sales configurators are set-up on a more or less procedural decision tree (at first choose the car model and then decide for an appropriate engine and gear, etc.).

Also in the domain of knowledge-based-engineering the rule concept is widely used. In contrast to the aforementioned knowledge-based systems, KBE aims commonly at the modification or analysis of a geometric product model which is available in a computer-aided engineering, especially computer-aided design system. On the one hand, many CAD-systems have the ability of using design rules directly in product modeling [20].

As an example, Autodesk Inventor Professional uses two different rule implementations. First, within the part modeling environment, the suppression state of a feature and a parameter may be linked via rules. In the example shown in fig.4 the cube’s fillet is suppressed when the length of the edge (described in a parameter named edge) exceeds 20 mm.

Another way of defining rules is the iLogic environment. The iLogic programming language is similar to script languages. Common constructs like if-then-else or select-case decision trees, while loops, the use of sub procedures and a class concept are usable. As command library the snippets include code templates for almost every modeling context within Inventor.



Name: Fillet1

Suppress

☐ Always

☑ If

Edge

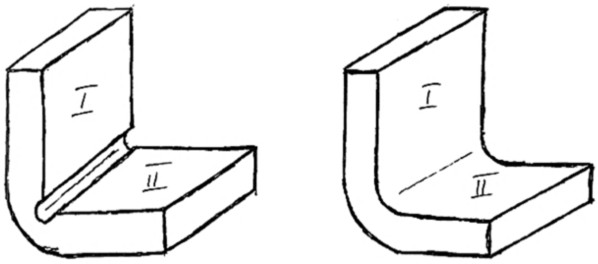
\>

20

Feature Appearance: As Body

Fig. 4. *Suppression state definition in feature properties dialog*

A use-case in this context is the formulation of manufacturing restrictions where rules are used to express explicit design knowledge that has a local influence on the surrounding geometry. E.g., when it is necessary to enclose a sharp-edged component within a hollow profile in extrusion molding the edge of the profile cannot be rounded as it is recommended. So, the rule can be formulated as depicted in fig. 5.



```
IF Face I AND Face II Guiding for sharp-edged Part THEN
  use Cut AND suppress Fillet
ELSE
  use Fillet AND suppress Cut
END IF
```

Fig. 5. *Definition of shape feature alternatives for extrusion profiles via design rule*

On the other hand, design support systems for adjacent design activities like manufacturing process design, tooling or fixture design embed rules. As example, Xuewen describes such a system for hammer forging design which was implemented as add-in for SolidWorks. Here, the rule-base is only one knowledge representation which is coupled with model-based approaches [21]. Hunter Alarcón synthesized a system for fixture design where the use of heuristic knowledge is similar compared to MYCIN. The system consists of a catalogue of standard parts for fixture design, an analysis system for the geometry of the machined part, multiple sets of rules for functional and detailed design and a model-base for functions and machining processes [22].

5. COMPLEXITY EFFECTS OF RULE-BASED SYSTEMS

Our analysis of rule-based systems on the aforementioned complexity measures leads to the following assumptions:

- Size of the possible solution space: When rules are used, the existing solution space is not affected regarding its size. When applied like in R1/XCON, rules check for the consistency of the targeted solution but generally do not invent new ones. When applied like in Hunter Alarcón's fixture design system, the rules lead to predetermined solutions which had been encoded in rules before. The generation of new inventive designs is not possible.
- Determination of the possible solution space: In principle, rules are able to address each of the variants within the solution space when used as decision tree. The limits of the solution space are clearly visible, there is no uncertainty within. On the other hand, when used as reasoning mechanism the exploration of the solution space is clearly structured but more flexible than in most of today's common web-configurators. Like in R1/XCON and MYCIN, rules may be used for coding control knowledge that extends the simple procedural approach.
- Degree-of-Exploration: Related to the determination, the degree-of-exploration rises when rules are used. Since all possible variants are addressed, there are no degrees of freedom inside the solution space. This may be complicated in parametric design because every parameter value range has to be expressed which results in a big hierarchy of rules pointing to the same parameter. The implementation of a decision table is a more compact formulation and has the same functionality. In terms of software engineering this concept corresponds to the select-case structure.
- Intersection of multiple solution spaces: Basically, the interaction of solution spaces is not effected by use of a rule-based system. As the same at the size of the solution space, the intersection is documented but not widened or reduced.
- Interaction of multiple solution spaces / overall system behavior: Regarding the interaction of different solution spaces, the context is the same as with respect to the determination. The system behavior is clear at all times since it is fully described by the rules. Nevertheless, as mentioned before, when rule-bases grow, the maintainability of the system declines. This is due to the fact, that every newly introduced rule has to be checked for consistency against the whole existing rule-base.

6. CONCLUSION

In the present article, the effects of rule-based systems on product complexity were discussed. Therefore, the Hannover House of complexity was introduced as a general framework for complexity management. For assessment, five measures have been presented that describe the possible design solution space for e.g. mass customization offers.

As noted before, the rule concept is one of the earliest implementations of knowledge-based systems and knowledge-based-engineering incorporated in an expert system. Today, rule-based concepts can be found in configuration systems, design support systems or in variant design automation. The fact, that rules are used as knowledge representation of heuristics and explicit design knowledge contributes to this.

By nature, product complexity can be reduced using rule-based systems since a solution space is formally described so that all possible solutions are known and in most cases the decisions of the reasoning are clearly visible.

Nevertheless, a rule-base is nothing else than a pure description of an existing solution space. Regardless of being created manually or automatically, the rule-base has to address every feasibly design either through a consistency check or a decision tree. Creative design is not their focus.

There exist a number of contributions which discuss the automatic generation of rule-bases for knowledge-based analysis systems, e.g. the assessment of a customer's credit ranking. A possible research question is how to transfer these fundamentals to KBE and synthesis systems respectively.

On the other hand, other KBE-mechanisms like constraint-based reasoning or case-based reasoning allow a different kind of formulation of solution spaces. These mechanisms of course have different effects on product complexity. Our present research targets on recommendations which KBE mechanism or product configuration approach is most useful for different types of business models.

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