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MODELING THE PORTFOLIO OF CAPABILITIES FOR PRODUCT VARIANT CREATION AND ASSESSMENT

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Abstract: *Choice navigation, solution space development and robust process design are the three mass customization key competences. The first and second are often mapped into product configuration or design automation systems and aim at specifying or co-designing a suitable product variant. Robust process design targets at managing a well-known but flexible supply network. As part of this, the portfolio of capabilities describes limitations to the solution space and is a valuable source of knowledge containing general design guidelines and specific manufacturing restrictions, like NC travelling distances, as well as availabilities of whole production processes. This article contributes a modeling approach that bridges solutions space development and modeling the portfolio of capabilities. Therefore, a knowledge-based engineering system is extended by a capability model of according production machines that allows to automatically check new product variants against the portfolio of capabilities and to estimate setup efforts and expenses of process changes.*

Key Words: ***Portfolio of Capabilities, Solution Space Development, Product and Process Configuration, Product Variant Assessment***

1. INTRODUCTION

Mass Customization is known as an umbrella for different business models that allow for individualization of products and services while being as cost-effective as mass production [1-4]. Successful mass customization depends on mastering three key competences, which are choice navigation, solution space development and robust process design, for which different implementation guidelines exist [5, 6]. The first and second are often mapped into product configuration or design automation systems that use techniques of knowledge-based engineering (KBE) and aim at specifying or co-designing a product variant [7-9]. Robust process design targets at managing a well-known but flexible supply network which spans a portfolio of capabilities [10, 11].

This portfolio has to be understood as limitations to the solution space and is a valuable source of knowledge containing general design guidelines and specific manufacturing restrictions for production processes and equipment [12]. The first are recommendations for product design regarding functions, shape design and geometric features that correspond to production processes [13, 14]. The latter are limitations to design parameter value ranges, like maximum NC travelling distances, hardening depths or handling weights in logistics [8].

This portfolio of capabilities and product design, or solution space development respectively, are strongly intertwined [15, 16]. Since manufacturing processes are subject to all kind of disturbances, all shape describing parameters of a product need tolerances [14]. So, the more accurate and precise a product feature needs to be manufactured, the higher are the requirements for the production processes. The actually realized dimensions can be expressed by probability distributions and the influence of uncertainties, like e.g. tool wear, change of environmental conditions or dissimilar properties of raw materials [16]. Managing these uncertainties referring to production is, as well as managing uncertainties in requirement fulfilment and market development, crucial to complexity management [17-20].

Modeling such a portfolio of capabilities in this context is still subject to research. Existing approaches predominantly use domain models and constraint satisfaction techniques in order to configure product variants and process chains together or extend a product solution space with service attributes [21-24].

The contribution of this article is a knowledge-based modeling approach for the portfolio of capabilities which is based on parts of the MOKA methodology (methods and tools oriented to knowledge-based engineering applications) [25]. The approach was tested in a real production environment for hairpin stators. The resulting KBE system allows to automatically check new product variants against the portfolio of capabilities, to optimize the product design accordingly and to estimate setup efforts or process changes.

The remainder of the article is organized as follows: In the following section 2, the theoretical background and related work is discussed regarding solution space development, robust process design and the interconnecting approaches of product-process and product-service configuration. Section 3 frames the research design while section 4 introduces the approach of a knowledge-based portfolio of capability model. In section 5, such a KBE system is exemplarily implemented for a wire bending process. Section 6 then presents the conclusion and shows avenues for future research.

2. THEORETICAL BACKGROUND AND RELATED WORK

2.1. Solution Space Development

Solution space development (SSD) is crucial for eliminating the apparent contradiction between individual product and mass production efficiency in a mass customization business model [1]. The solution space defines the choices, degrees-of-freedom and options that the customer determines in the co-design process [26]. It is stable over a long time and is developed with respect to responsive production and distribution of variants [27]. Regarding the discussion of the design solution space itself, refer to [8].

From a product engineering point of view, two areas are relevant for SSD. On the one hand, design methodological approaches guide developers in planning of a solution space and its elements. To those belong:

- <u>Product Family Design</u>: Product families share common features and components accross multiple product variants [28]. The idea behind is to reduce variant-induced costs due to allowing only distinct components to vary [19]. In this context, a product platform refers to the combination of components and the necessary interfaces which provide basic functions for a large number of product variants [29].
- <u>Modularity</u>: A module is generally a self-sufficient, separable building block, which fulfils defined functions [30]. Modules can be designed, manufactured and validated independently from each other and the later configured product variant [14]. An important focus during development is the definition of interfaces between the single modules. An accurate design offers not only the possibility of exchanging faulty modules during maintenance, upgrading the product through improved modules or quickly dismantling a product for disposal [31]. It also influences the size of the possible solution space due to the combinatorial manifold [32]. Different types of modularity may be distiguished from each other, e.g. component swapping modularity, cut-to-fit modularity or bus-modularity [27].
- <u>Design Parameter Variation and Forward-Variance Planning for Multi-variant Products</u>: Design parameters are a concept that was developed in the 1990s to describe geometry independently from dimensions and technical features [33]. Design parameters are topology, shape, dimension, count, sequence, tolerances, material and surface finish [34]. A corresponding variant design methodology uses alteration rules to these parameters that, e.g., guide the user in changing the sequence of machine elements or to change the topology of a structural component in order to explore the solution space and find a superior design. This concept was adapted and translated into a specification language for multi-variant products in order to combine design parameter variation and solution space development [35, 36].

On the other hand, for the modeling of solution spaces in computer-aided engineering environments, there are different options:

- <u>Design Prototypes and Templates</u>: Commonly, the solution space is understood as a set which contains different designs that fit to a set of requirements. The concept of design prototypes reverses this as it represents a space where a design artefact may be altered in a certain way [37]. Years before parametric computer aided design systems became standard, three of their bascic principles had been postulated: Parametrics, feature-based design and templates [8]. Such templates usually accumulate several model elements into a reusable building block of a computer aided design model [38]. Therefore, a template implements task-dependent knowledge of previous development projects and a scheme how it is applied to a new situation [39].
- <u>Knowledge-Based Engineering Systems</u>: KBE systems are computer-aided problem-solving tools for engineering tasks [7]. KBE systems for product design use computer aided design, object-oriented programming and techniques from artificial intelligence to e.g. automate routine design tasks [40]. Instead of individual product variants, a common master model is set up as an image of the solution space. Technical product configurators also belong to KBE systems [41].
- <u>Design Automation Systems</u>: As particular type of KBE systems, design automation systems fully automate a design task from specification over conceptual design to detailed design and definition of product and production data [3, 42].

2.2. Robust Process Design

Robust process design (RPD) focuses on the ability to quickly connect organizational units and resources in order to configure a customer order-specific value network [27]. In important point is to understand the value network as portfolio of capabilities that describes limits to the possible solution space since it is a source for design guidelines and manufacturing restrictions to be used in solution space development [8].

Here also apply two avenues for action. First, there are organizational and operations management approaches relevant for RPD, like:

- <u>Postponement</u>: In order to organize manufacturing operations towards efficent realization of product variance, postponement means to shift the order penetration point towards the end of the production process [43]. As a result, all manufacturing stages before this can be treated as standard variants [44].

- Cross-domain and Cross-Enterprise Information and Knowledge Sharing (IKS): IKS can be seen from three perspectives [45]:
  - KS in product development allows to quickly deliver customer requirements, demands and habits with the goal of speeding up new product development and introduction.
  - IKS in production assures supply chain coordination and optimization of daily operations and responses.
  - IKS in operations and finance strategically integrates manufacturer and suppliers.
- Supply Chain Coordination and Supply Network Management: In order to organize for product variability, manufacturing needs to be set up as flexible, redundant production units which offer their resources to the organization. Scheduling, decoupling and optimizing the trade-off between variety and costs are the major points of interest here [9, 10]. Needs and goals must be coordinated and mediated accross different units either in the same or across multiple companies [46, 47].

Second, approaches for modeling and computer aided development of portfolios of capabilities exist, which are to be understood as related work for the approach discussed in this acrticle:

- Resource-based Configuration: This is a special configuration approach that is dedicated to balancing resource allocation and consumption in a technical system. Resources are abstractions of relationships between components and / or their environment. The approach may be applied for supply chain organization [48, 49].
- Product-Process Configuration: This approach integrates a model based on three domains: Selectable product features and their characteristics are formulated and matched to product components or features which are connected to the manufacturing processes used to produce and assemble the individual product variants. For each production process chain, operational resources like production equipment, tools and also processing time may be assigned. Properties, components and process chains are formulated as a constraint network [21].
- Product-Service Configuration: In this approach, the geometric CAD model of an assembly is taken as a basis to model accompanying services like maintenance activities. Since the CAD model describes the neighboring relations, build structure and parameters, the implementation of service knowledge by additional constraints and service parameters allows to calculate and modify single service tasks. E.g. the time for dismantling an assembly to change a wear part is then evaluated by the disassemble sequence from the CAD model, stored times for processing a component and the number of occurrences of screws. Together with information about service life of single components, a graph database is then used afterwards to model the single service activities, group activities to a service and optimize the information exchange between product design and service engineering [24, 50].
- Case-based Parametric Analysis: Although not meant as an approach to model the portfolio of capabilities, the computer aided engineering environment created here delivers valuable insights how restrictions from a new process chain can be fed back into design. The idea is to design parametric design templates that are varied in a controlled manner to evaluate the sensitivity of a parameter change on mechanical properties, like e.g. the stress distribution. In parallel, the same is done for the corresponding manufacturing process to formalize the interdependencies of e.g. tool shape, machine parameters and cycle times. The specimen created here are analyzed and fed back into the design system. The mediator between design and manufacturing is a case-based reasoning (CBR) system where each configuration is stored, independently from being realizable or not. When now a new part is designed, the CBR system is able to identify optimized designs based upon similar feasible cases from the past or create advices to adapt e.g. tools. The system was validated for a complex multi-material process chain [51, 52].

3. METHOD

The research design follows the methodological recommendations of Stokes [25] for the development of knowledge-based engineering applications with a focus on the later stages of the MOKA lifecycle, i.e. capture, formalize, package and activate.

During *capture*, all necessary knowledge entities need to be collected, knowledge sources must be identified and validated. Since the knowledge is until then still available in an unstructured manner, *formalize* aims at implementing a formal, machine readable knowledge model. For both stages, MOKA proposes the applications of so called ICARE diagrams that structure engineering knowledge in product (entities and components), process (rules and activities) as well as linking knowledge (illustrations). *Package* and *activate* then target at implementation, test and roll-out of the KBE system.

The following section integrates the development of the knowledge-based portfolio of capabilities model to the above MOKA knowledge models.

4. KNOWLEDGE-BASED PORTFOLIO OF CAPABILITIES MODEL

A manufacturing task may be basically described as process where an input workpiece is transformed into an output workpiece using resources, i.e. the production machines, jigs and other operational resources. The manufacturing process chain is thus a combination of several of such processes. The according scheme is depicted in figure 1.

4. Definition of a workflow design: Who are users of the later KBE system and what outputs are necessary here (related to MOKA *Package*)?
5. System integration, user communication and interface design: In which software environment the system is to be implemented, how are outputs communicated to the user and what are test scenarios for validation (MOKA *Activate*)?

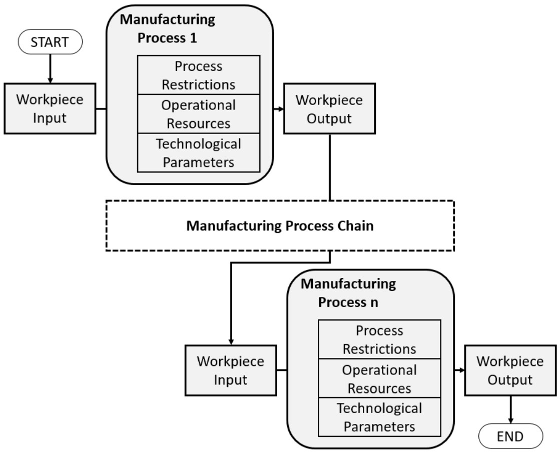


Fig. 1. *Manufacturing Process Chain Representation*

A portfolio of capability model needs to represent these relations in a generic way in order to assess if a part or assembly can be output or not. The MOKA ICARE diagrams may be adapted therefore: For each single process, process restrictions, from which design guidelines may be derived (e.g. travelling distances of a milling machine), operational resources (e.g. jigs, tool inserts) and technological parameters (e.g. feeding speed in relation to material and targeted surface quality) are implemented into the process part of the knowledge model. The formalization is related to the later purpose: If the portfolio of capabilities model is e.g. used as a design checker, then model- and rule-based mechanisms are beneficial that can process either input parameters or a CAD file and its incorporated feature tree and parameter list. If the model should additionally deliver data about process parameters and the setup of the according machine, CBR or other database related approaches may be used.

The product model describes work piece input and output as well as mechanisms that allow to derive manufacturing operations from geometry, i.e. feature recognition capabilities or a simple generic feature list which is related to manufacturing operations.

The connection of single processes to a process chain is also formalized by geometric and parameter data and corresponds to the linking knowledge as described in MOKA. Thereby it needs to be maintained that an output of a process and the input of the succeeding process are compatible.

For a known manufacturing process chain, the following five steps thus need to be performed to model the portfolio of capabilities:

1. Design of the Process Chain Knowledge Model: Which manufacturing processes are available for a manufacturing task, what machines and tool sets are involved therefore and which operational resources are necessary and what are inputs and outputs?
2. Formalization of individual process models: What are process restrictions, technological parameters for setup or tolerances and individual operational resources?
3. Formalization of the input knowledge model: What are semi-finished products, what are available tolerances?

5. APPLICATION EXAMPLE

The approach was tested in a real life production environment of a manufacturer of electrical machines. Part of the product portfolio is electrical drives. Beside traditional wiring and winding, product series that use the so called hairpin technique are manufactured in large, but varying batches. The market of such drives is currently developing and strongly growing due to the demand for e-mobility [53, 54].

It was agreed to test the portfolio of capability modeling approach for a line that is very basic for production which is the preprocessing of enameled copper wire to the hairpin (Figure 2). The production process chain contains the basic steps feeding from cable roll, skinning (removing the isolation), cut to length, bending, and forming [55, 56].

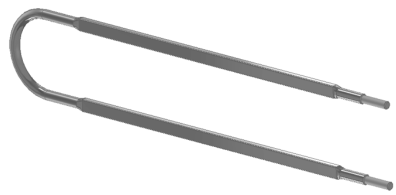


Fig. 2. *Pre-manufactured Wire for Hairpin Stator*

Depending on the electrical properties of the drive, the dimensions of the hairpin change from series to series but the production process itself remains more or less constant. Degrees of freedom consist for changing of single tool sets (e.g. cutters for skinning and forming dies), adapting process parameters (travelling of bending fingers or forming pressure) or switching between two alternative bending processes.

5.1. Process Chain Knowledge Model

The first part is the representation of the process chain itself. Therefore, a station list was implemented that contains each production machine for a manufacturing stage of the process, existing alternatives and the set of operational resources (e.g. tool inserts, consumables). The list is then taken as a basis for configuring the individual process chains. With this a basic estimation of production costs is already possible and so the comparison of different setups.

5.2. Individual Process Knowledge Models

For each individual process step, another more specialized knowledge model is implemented which is discussed here for the bending processes of the hairpin. Two types of tools are considered in this example, i.e. roll bending and die forming. Both types of tools allow bending the wire in one plane which is sufficient for most applications.

CNC roll bender and wire forming machines use a bending mandrel or claw to give the wire its shape. The bending machines, which are often NC-controlled, allow quick and easy parameter changes and compensation of manufacturing tolerances. However, this flexibility is usually at the expense of cycle time. The enameled copper wire coming out of the straightener is fed between a bending mandrel and a counter support by an NC-controlled feed. The actual bending is then performed around the mandrel, controlled by a rotating roller. The bending mandrel around which the bending is performed also determines the bending radius. The bending angle is determined by the traversing angle of the bending tool, which is flexibly adjustable via the machine control. Bending tool and mandrel are provided with grooves matching the wire diameter to avoid flat spots and marks on the wire. The leg lengths can be controlled by traverse paths of the NC feed. In the last step the wire is cut off at a defined position.

To this, die forming is different: After being fed into the open tool the wire is fixed and cut off. Then the forming process takes place as the punch closes and the wire is formed over the positive and negative mold. The diameter of the wire as well as the bending angle and bending radius are determined by the tool shapes and are fixed. This process is therefore well suited for highly clocked mass production with stable processes where flexibility is not required.

Usually, for both processes, a tolerance window must be investigated and defined for the specific wire and the bending radius, in which the process can be operated deviating from the nominal dimensions of the tool by manual override of a process engineer. This is e.g. done in pilot runs or during running in the mass production process. Based on these two tool examples and identified parameters, a knowledge-based process configurator is now provided, in which the two types can be stored as tool sets in order to check manufacturing possibilities of known tools for the process.

By analyzing the tools and the process, the following geometric parameters need to be formalized among others:

- Minimum / maximum bending angles and working area
- Minimum / maximum bending radii
- Minimum / maximum leg length
- Wire diameter (fixed for die forming)
- Layout and sequence (fixed for die forming)
- Change to cross-section (only for die forming)

Additionally, technical parameters for process control need to be considered, like cycle time, applied forces and pressure, temperatures etc. These are formalized with respect to machine-tool-combinations and have also a tolerance range in order to consider wear. Since these parameters are highly sensitive to the individual production process and rely on the experience of the production engineers, this is core know-how of the manufacturer and will not be further explained.

5.3. Input Knowledge Model

As discussed, an important part of the knowledge model is the formal representation of the semi-finished materials that are the input for the manufacturing chain. Enameled copper wire is a copper wire with a partially multilayer insulating enamel coating. This is available in different shapes (round, square) and with different copper diameters and enamel thicknesses. The wires are produced in large quantities and supplied on cable rolls with several hundred meters of wire on them. The wire itself is narrowly tolerated in diameter and form. Non-equal cross-sections (e.g. rectangular) make particular requirements for feeding mechanisms. Thin enameled copper wire (<0.5mm) is often used for winding coils, thicker wire is often used to produce hairpins. Beside the geometric properties of the wire, its material characteristics and forming parameters must be implemented into the knowledge model, e.g. to determine if a bending diameter can be realized without damaging the isolation or the wire itself. A valuable source of knowledge is the flow curve (true stress over true strain or deformation degree) that describes the forming behavior of a material. All data, necessary calculations of single material properties as well as ordering and supplier information is stored in a wire catalog.

Additionally, shape describing parameters are determined for each manufacturing stage and documented in a corresponding parameter hierarchy and fixed nomenclature.

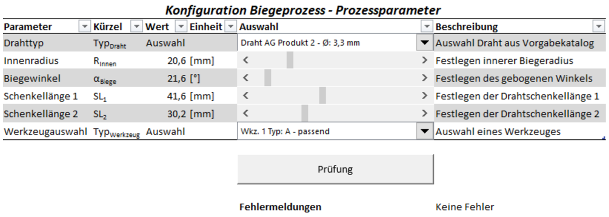
5.4. Workflow Design

Together with manufacturing specialists and the design department, two basic workflow designs were committed. The first is tailored for the production engineering for assessment of a new hairpin variant. Here, besides the technical drawing, a form containing geometric parameters is handed over that should be directly imported into the KBE system. The system then should find a corresponding wire from the catalog (or alternatives), then check bending radii, angles and leg lengths and afterwards search for process chains. In case that e.g. no tools are available, the user should be able to define parameters to be varied in a known tolerance window which are then processes by the KBE system. If a feasible design is found, the optimization is fed back to the design department for approval. After release of the geometry, the KBE system should output the process parameters as a first basic setup for the production machines. Made experiences should be able to be fed back into the system and stored as corrective factors. The second workflow focusses on the design department and incorporates a downsized interface and also the parameter check and optimization tools from the KBE system.

5.5. System Integration

Since the manufacturing layout is basically fixed, a static approach for the KBE system was chosen. All knowledge models were implemented in spreadsheet-based configurators which were enriched with necessary macros for calculation and the mentioned parameter variation and optimization.

The geometric data is imported via xml-file and processed into the check dialog as shown in figure 3 for the design-centered workflow. The sliders hereby indicate the location of the parameters relative in the corresponding process window. After the check, error messages or hints for optimization are output below the check button.



Konfiguration Biegeprozess - Prozessparameter

Parameter	Kürzel	Wert	Einheit	Auswahl	Beschreibung
Drahttyp	Typ_{Draht}	Auswahl		Draht AG Produkt 2 - Ø: 3,3 mm	Auswahl Draht aus Vorgabekatalog
Innenradius	R_{Innen}	20,6	[mm]		Festlegen innerer Biegeradius
Biegewinkel	α_{Biege}	21,6	[°]		Festlegen des gebogenen Winkels
Schenkellänge 1	SL_1	41,6	[mm]		Festlegen der Drahtschenkellänge 1
Schenkellänge 2	SL_2	30,2	[mm]		Festlegen der Drahtschenkellänge 2
Werkzeugauswahl	$Typ_{Werkzeug}$	Auswahl		Wkz. 1 Typ: A - passend	Auswahl eines Werkzeuges

Prüfung

Fehlermeldungen Keine Fehler

Fig. 3. *Imported Geometric Parameters and Location in the Process Window.*

The production-oriented input interface contains more parameters and the possibility to define tolerances etc., and to assess the suitability for a distinct tool set. This assessment environment compares the required values with the limits of the process. The test result is shown as traffic lights:

- <u>Status "green"</u>: The target geometry may be produced on the actual line with minor changes: (1) Modification of controllers and call/check of new control program, (2) defined tool or machine modification with available hardware adjustments or actors, (3) tool exchange with set-up time less than 15 min.
- <u>Status "yellow"</u>: The target geometry may be produced on the actual line with major changes: (1) Tool exchange with set-up time between 15 and 120 min, (2) minor modifications to the base station, (3) newly designed tool insert or hardware modification of tool necessary.
- <u>Status "red"</u>: The target geometry cannot be manufactured on the actual line without layout changes or major modifications to a station: (1) Tool exchange and set-up time more than 120 min, (2) major modification to the base station or exchange of a base station.

As the KBE system also contains information about tool and set-up costs, a corresponding estimation can be output as basis for decision-makers whether a change is justified in relation to the expected production output.

6. CONCLUSION AND FUTURE RESEARCH

It took about four months for a knowledge engineer to implement the system with help of senior production engineers and specialists from the job shop. This is partly explained by an iterative modeling approach. An initial KBE system had a too low resolution for single process steps so that a subsequent adjustment, validation and feedback of the machine parameters was necessary. The final version of the KBE system then met the expectations. As a result, the running-in times of the production line could be reduced in some cases to 30 % compared to the initial situation. For the coordination between the development department and production, the effect is similar. Additionally, the KBE system proved as a foundational tool for an objective discussion of features between product design and manufacturing.

Regarding the implementation, a static approach was chosen and proved itself as sufficient for the task. But this is only advisable, when a fixed line layout in the job shop is installed. In the case of flexible manufacturing systems, more flexible implementations need to be chosen accordingly. A concept for this may be the application of multi-agent systems. In the last two decades, such systems were already proposed for the orchestration of manufacturing systems and the optimization of a part regarding design for manufacturing [57-60]. As communication and coordination mechanism between the sub-systems, ontologies might be an interesting approach and an avenue for further research.

Another interesting observation in the case study project was that solution space development was indirectly implemented into the design department. The portfolio of capability model describes the limits of the solution space and allows conclusions about an optimal design under given boundary conditions or optimization goals, e.g. minimizing set-up efforts in production. Remarkably, there was no necessity to define a product family or to change the product structure to modular, so the existing methodological approaches for solution space development were in fact extended. A further question is how this can be formalized into a design methodological support framework. Starting point here might be the DfX (Design for eXcellence) approach which is further concretized by the portfolio of capability model.

At last, it could be shown in this project that KBE systems and configuration paradigms are beneficial in production planning also for mass production. A conclusion here is that such KBE systems allow for examining the robustness of a production line to design changes or to disturbances due to varying parameters. If this is also advisable for complex production processes has to be investigated.

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