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Design method for cost-effectively realizing high variety products

Robbert-Jan Torn[a,]*, Tom Vaneker

[a]*University of Twente, Dept. Design, Production & Management, Drienerlolaan 5, 7522 NB Enschede, The Netherlands*

* Corresponding author. *E-mail address:* i.a.r.torn@utwente.nl

Abstract

During the last decade, the European manufacturing industry has experienced a growing trend towards customization and personalization. As a response to increasing global competition and changing customer needs, there has been increasing attention to achieving shorter time-to-market, and manufacturing products for smaller market segments. Throughout this paper, the term 'high variety products' will be used to describe products that contain at least one product part with a customized geometry. There are two primary aims of this study. First, to illustrate the current challenges that Small- and Medium-sized manufacturers face with high variety products. Second, to explore how these challenges can be addressed systematically. Assembly tasks within existing manufacturing systems for high variety products typically involve a combination of manual labor and automatization. As geometrical variation is considered complex for automation, cost considerations can hinder increasing the level of automation in assembling high variety products. However, this objection might not be legitimate. Hence, this paper proposes a new design method to improve decision making for cost-effectively realizing high variety products. Two core findings of this study include: First, the achievable product variability of a production process depends on the process step least robust to geometrical variation. Second, the adjustability of product design is regarded as an enabler for customization and increased automatization of the production process.

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Keywords: Design Method; Automation; variety; Industry 4.0; Manufacturing System

1. Introduction and aim of the research

Increasing global competition requires manufacturers to re-evaluate automatization to unite two possibly conflicting objectives: decreasing time-to-market and production costs and increasing quality and product variety perceived by customers. The need for addressing this dilemma is reflected by practitioners, part of present competitive strategies for the manufacturing industry, and similarly indicated by the increasing amount of scientific literature on Industry 4.0 and mass customization. One of the challenges of Industry 4.0 is a transition from mass-produced goods in large volumes (the common scenario during the 3rd industrial revolution) to cost-effectively realizing products in lot-sizes of one [1]. In the ongoing development towards smaller series production batches and higher product variability, under which Mass Customization (MC) can also be assigned, lot-sizes of one can be considered the ultimate goal in terms of variety. MC literature indicates that catering products to small market segments, up to individual customers, increases the willingness of customers to pay a price premium due to increased customer satisfaction [2]. Naturally, not all mass-produced goods will be subjected to this change towards high variety, as not every product that can technically be customized leaves much room for demanding a price premium for customization. It can be expected that the exact margin depends on the industry in which a company operates and is further affected by the subjective relationship between costs and the perceived added value of high variety. Another consideration is that although products might be perceived as unique by customers, from a manufacturing viewpoint the uniqueness could be limited. Throughout this paper, the term 'high variety products' will be

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used to describe products that contain at least one product part with a customized geometry. In summary, this research incorporates a design method that is aimed at products that have a high degree of internal variation concerning their geometries, but which all undergo approximately the same steps in the production process.

During the 3rd industrial revolution production automation became the standard for a subset of mass-produced products. Next to the production processes themselves also part handling steps became automated. Much effort was needed to streamline the product design, production steps, and in between product handling operations. Dedicated production lines were designed and optimized to produce many products at low costs. The 4th industrial revolution now among others focusses on the methods and tools for self-regulating and optimizing production processes (amongst others supported by sensors, (collaborative) robots, IoT, cyber-physical systems, cobots, AGV's, vision systems, and adaptive fixtures) that will enable short series production of geometrically unique products at the cost of mass production [3, 4].

While the development costs of automation under the 3rd industrial revolution were distributed over many products, the new flexible production facilities can only realize the same if these self-optimizing manufacturing systems can handle a wide range of products without the need for costly human control, optimization, or re-organization. To optimize the product creation process to meet these latest standards, the product designers need to optimize product design to all product handling views associated with I4.0. The product design should be optimized for the whole product development chain and not just focus on the production and assembly stage. A structured design method is needed that extends DFMA to include I4.0 in product development systems. It should enable the designer to see past production towards the effects of decisions on all product-related steps and should help in evaluating choices related to value and total product development costs.

2. Examples from Industry

To illustrate the type of challenges our design method applies to, three examples from industry are presented. These three cases have been used for identifying similarities and differences between the current situation at the companies investigated (e.g. do the companies encounter comparable challenges?).

Company A creates sheet metal products from laser cut metal plates that are bend and spot welded. Their one-off/ small series products are manually welded while medium-sized series (20-500) are manually loaded on dedicated fixtures, to be welded by a welding robot. For automating this production process, a handling robot should present the next plate to be welded. Due to the plates rolling direction and its orientation towards gravity while being lifted, the plate will deform. In manual production, this deformation will be noticed and counteracted by the human worker. When automation solutions are envisioned to tackle this problem, vision systems could be installed and trained to determine the deflection and instruct the robot on how to re-orient the plate to reach the proper welding solution. But a redesign of the plate into smaller sections could minimize deflection. Also, the plates themselves could be designed to have self-aligning features so deflection can be counteracted without the need for active control of the production system.

Company B produces valves for the oil and gas industry. Their current production portfolio contains 9 types of valves with numerous possible variants per type. The valves are produced on-demand in series sizes ranging from 1 to 100. Their current assembly process is manual where automation of that process has operational and strategic advantages. One of the steps of the assembly process is the placement of the plug that fixates the shaft/valve assembly. The different valve sizes and materials all require individually unique plug dimensions and torque. For manual assembly, this is no problem, but for automation, this increases the complexity of among others plug storage and resupply, robotic handling, torque control, and camera-based quality inspection. Using the same plug for all valves would reduce automation complexity but would require product redesign and would increase the material costs of the plugs and valves.

Company C produces safety shoes for workers in various industries. Key to the production processes are the shoe lasts that determine the geometry of the safety shoes. Currently, the shoe lasts come in 10 sizes that each are available in 3 widths. The assembly line is set up to produce series sizes of around 100 shoes that use the same size last. But this limits the flexibility of the production process. As the production process cannot dynamically adapt to lasts in different sizes, for some operations the parameters need to be changed. A transformation towards smaller series sizes would in the current situation lead to more frequent changeovers. However, not every production step is equally affected by these changeovers.

Summarizing, the three aforementioned examples from the industry show that some manufacturers that have already established a high product variability struggle to further automate their production process. In contrast, other manufacturers have achieved a higher level of automatization but are challenged by incorporating geometrical customization in their product portfolio. Overall, the assembly systems at the invested companies all combine manual labor with some form of automation. All involved companies were convinced by increasing the level of automation as a strategy for saving costs. Meanwhile, the three companies also acknowledged the difficulty in decision making to determine the next step towards increased automation.

In this paper, we argue that product design can be used to customize its geometry and simultaneously to enhance the automatization of the production process. It could, for instance, be the case that small changes in the product design or the production process facilitate a transition from manual labor to automation for some operations. Such changes expectedly lower the threshold for cost-effectively realizing higher levels of product variety in manufacturing and assembly. In identifying opportunities for decreasing the threshold for cost-effectively realizing high product variety, this research proposes to define a method for design engineers that satisfies the following three objectives:

- Allows to evaluate the applicability of the current product portfolio with production and automation scenarios;
- Proposes optimized redesigns for the products to improve that product for later product developments stages; and
- Allows evaluation of the effects of these product modifications against benefits in the production automation stages.

3. Literature review

In addressing the requirements of the method, the literature review incorporates the following two topics: Methods that allow for a systematic review of the current product portfolio, and product design optimization methods.

3.1 Relevant production assessment approaches and their limitations

Most of the available production engineering assessment tools are quantitative and related to lean production/ lean manufacturing [5]. Qualitative methods do exist, however, but are often not publicly available or not published in the English language whereby a critical reflection is obstructed. Previous studies (e.g. [6], [5, 7]) present valuable overviews by comparing existing production analysis methodologies as part of their justification for developing a new methodology.
According to a comparison between manufacturing system analysis methods made by the authors of the Productivity Potential Assessment (PPA) method, assessment methods can be divided into three categories: (1) internal audit (conducted on-site by personnel with the same company); (2) external audit (conducted on-site by independent analysts), and (3) self-assessment (conducted off-site through questionnaires or interviews) [5]. Their comparison shows that different methods are suited to different applications and goals, depending on the time available and the desired depth of study. Nonetheless, the quality of data collection on-site remains difficult to replicate through interviews. Namely shop floor observations provide invaluable information from discussions with operators about their experiences and suggestions that would otherwise be discarded.

In developing a production assessment method, the shortcoming of previously established methods should be considered. Four common ways of how currently available production analysis tools fall short in supporting companies in assessing and improving production systems include [7]: (1) Models that exclusively focus on production output contain the risk of losing track of the overview that connects the results; (2) Tools that adopt a broad scope of assessment (e.g. by covering the entire supply chain) tend to be challenging to use and require training; (3) Tools with a broad scope tend to lack concrete advice for improvement; (4) Many assessment methods mistakenly assume generalisability by overlooking the context and type of companies to which the method applies. Most production analysis methods that make use of external auditing, predominantly use hierarchical tasks analysis (HTA) for identifying and describing the main operations and sub-tasks. HTA originates from scientific management literature and has a range of applications, including job design, workload assessment, and interface design [8]. HTA is well suited for describing production processes because it breaks down processes and links sub-objectives and actions and tools to achieve those sub-objectives [9]. One of the most extensively documented production assessment methods is the Dynamo method, an assessment tool from the 2000s that determines the level of automation of production systems and identifies future automatization opportunities [10]. Central to the Dynamo method is expressing the task division between the human and the machine as a variable, designated as the level of automation. Ultimately, the Dynamo method uses the identified levels as requirements to judge the potential of future automatization concepts.

However, the results from analyzing and describing a production system do not prescribe instructions for further optimization. To come to a redesign, knowledge is needed to recognize opportunities for further automation. This concerns both product development and process redesign. Since existing production analysis methods are mainly focused on the production process and less on product development, the possibility of adapting the design of the product has remained an underexposed aspect. To get the necessary knowledge for redesign and to integrate this in our method, we consider design for assembly principles and the state of the art.

3.2 Product design optimization for high variety products

To cost-effectively realize high product variety, manufacturing systems need to optimize external variety versus internal complexity [3, 4]. Based on functional and behavioral modeling, this can be expressed as aligning the functional requirements of the products to be manufactured with the set of the behavior of the available manufacturing resources [5]. Most product variability is realized in the final assembly, where the proportion of manual labor is the highest of all assembly stages [11]. Due to the complexity of assembly, for many operations, human workers are still the most efficient solution [12]. Especially in adapting to variations humans are much more capable than automatization solutions and will produce a more stable output than machines.

Many researchers have attempted to develop tools for improving the ease of assembly, of these methods DFMA has become one of the most well-known. DFMA considers manufacturing early in the product development process to, amongst others, shorten product development time, increase product quality, and accelerate time-to-market [13]. The motivation behind DFA is that designing individual components with the ease of assembly in mind can reduce assembly time significantly. This leads to savings in both material and human resources [14]. Likewise, when DFA guidelines are ignored in the product design process, the downstream production complexity and costs might increase and thus lower the overall product satisfaction.

Improving existing product designs based on the initial CAD file often leads to proposed modifications that are close to the initial design [15]. As DFMA guidelines tend to be limited to deleting fasteners and merging existing parts, opportunities for improving product performance in addition to ease of assembly might be overlooked. In recent years, this limitation has received growing attention due to the emergence of additive manufacturing (AM) as a state of the art. One advantage of AM over conventional manufacturing is the design freedom for creating complex geometries to increase functionality and improve performance [16]. Due to the absence of form restrictions, Design for additive manufacturing guidelines are fundamentally different than DFMA and requires designers to explore unconventional designs. The global design approach by [15] aims to overcome the difficulty in determining how a CAD model designed for conventional production processes, can be optimally redesigned for additive manufacturing. We argue that the same line of reasoning (i.e. by re-evaluating the essential aspects of a product geometry) can be applied to redesigning high variety of products with improving the ease of automatization in mind.

The aforementioned design approach was further developed into a part consolidation method that consists of two steps: function integration according to functional requirements, followed by structure optimization to further improve the functional performance of the product [17]. An underexposed aspect of this part consolidation method, however, is process constraints.

4. Proposed Methodology

4.1. Development of the method

In developing the design methodology presented here, inspiration was drawn from both the Dynamo method and the part consolidation approach by Yang et al, as mentioned in the previous sections. However, compared to existing methods (and e.g. the general engineering process) the method presented here differs in two ways. First, our method is specifically aimed at evaluating the applicability towards high variety products within existing product portfolios. Second, rather than incorporating the complete product life cycle, the method presented is limited to improving decision making.
The goal of the design method is to provide a systematic approach for analyzing a production system and redesigning products for high variety while taking the available resources of the production process into account. Hereby two main inputs are considered: the requirements of the product, and the available manufacturing resources. The design method as shown in figure 1 consists of 4 steps that will be discussed accordingly in the following sections.

The envisioned outcome of the product analysis is a well-defined design space that provides insight into the extent to which the geometry of the product is allowed to change, while still meeting its functional requirements.

The product analysis starts by determining the scope of analysis (i.e. the product- or product line) in consultation with the client company. Next, the product is decomposed into product parts whereby for each product part the number of variations is

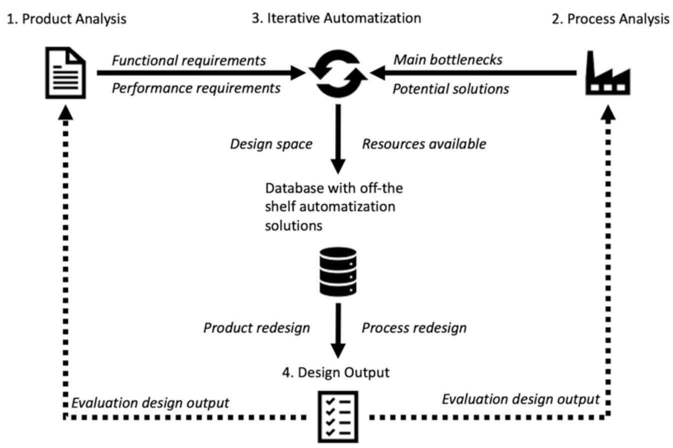

Figure 1 Visualization of the design method and its respective execution steps

inquired. In essence, products consist of a collection of product parts assembled. These product parts develop from elementary starting points to parts by transforming. Some of these transformations are aimed at realizing the product, but additional transformations are needed to facilitate the production process (e.g. by creating a geometry that allows for robotic handling, or by adding reference points for recognition by vision systems). Thus, information is needed on how the characteristics of product parts affect each other (e.g. using an overview of compulsory/ allowable/ prohibited combinations of product parts). Thereafter, the performance requirements need to be formulated (e.g. by expressing essential tolerances and how these are measured). Ultimately, it can be determined when which of the functional requirements are met during the process analysis.

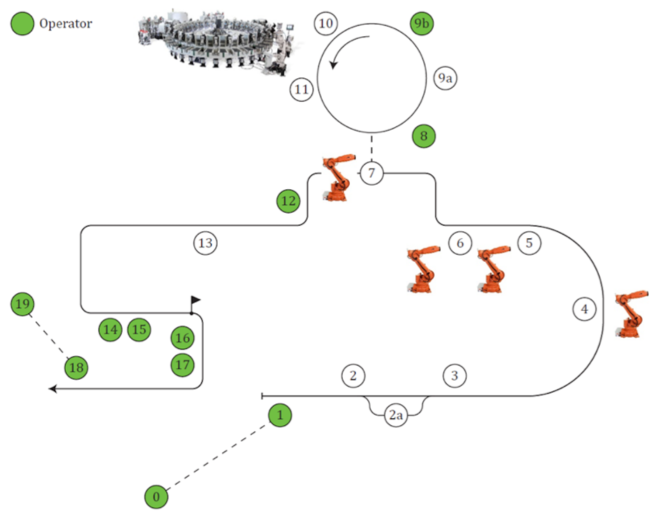

Figure 2 Outcome of process walkthrough company C

4.2. Process analysis

The second step of the design method is a process analysis. The process analysis identifies the operational challenges of the process steps, or workstations, that will be most affected by an increase in product variety. The process analysis consists of 3 steps: a walkthrough, a detailed observation, and a functional decomposition.

The process analysis starts with a walkthrough of the process steps that correspond to the previously determined scope of analysis. The walkthrough is preferably conducted under the supervision of an operation manager while the production line is up and running. This provides room for discussions with operators to identify their views on existing problems and potential solutions. Figure 2 shows the result of a process walkthrough at company C.

Thereafter, a detailed observation is conducted to identify the sub-steps of each process step. For manual process steps a comparison is made between observing the operators and the work instructions, as it could be the case that some operations are not documented but performed by operators to correct for mistakes earlier in the process. Corrections for mistakes might include rotating-, touching up-, or reattaching a product part. We define such correcting operations as ‘implicit operations’ as they are based on experiences of operators rather than process documentation. These implicit operations need to be considered in setting requirements for a redesign. For automated production steps, each action that results in a change (e.g. decision making, rotation, movement) is documented. Figure 3 shows the detailed observation of one process step at company B. In this example, the manual assembly process for the tightening of a threaded plug and sealing ring involves the sub-steps a to h.

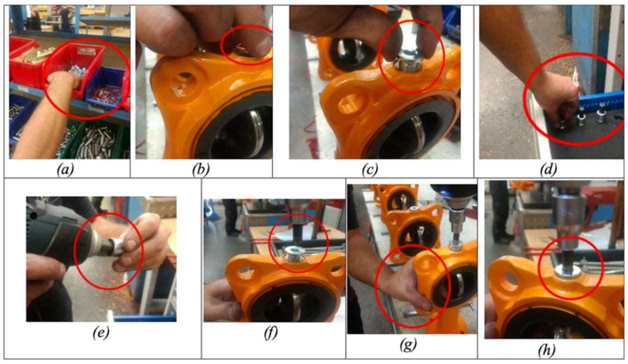

Figure 3 Manual assembly process at company B

4.3. Iterative automatization

After conducting the detailed observation, a process decomposition can be made. Figure 4 shows an example of a process decomposition in which process steps are decomposed into three consecutive levels: the functional-, the operational-, and the kinematic level. Hereby, the functional level separates process steps and describes each process step by stating its goal. The operational level specifies for each process step its starting condition, its final condition, and what action it takes to achieve this final condition. The kinematic level is defined as a single state change facilitated by one piece of hardware, validate by one sensor, and controlled by one parameter. The idea behind decomposing production steps to their most rudimental level is to simplify complex tasks to tasks that are small enough to easily identify the requirements to automate these small steps.

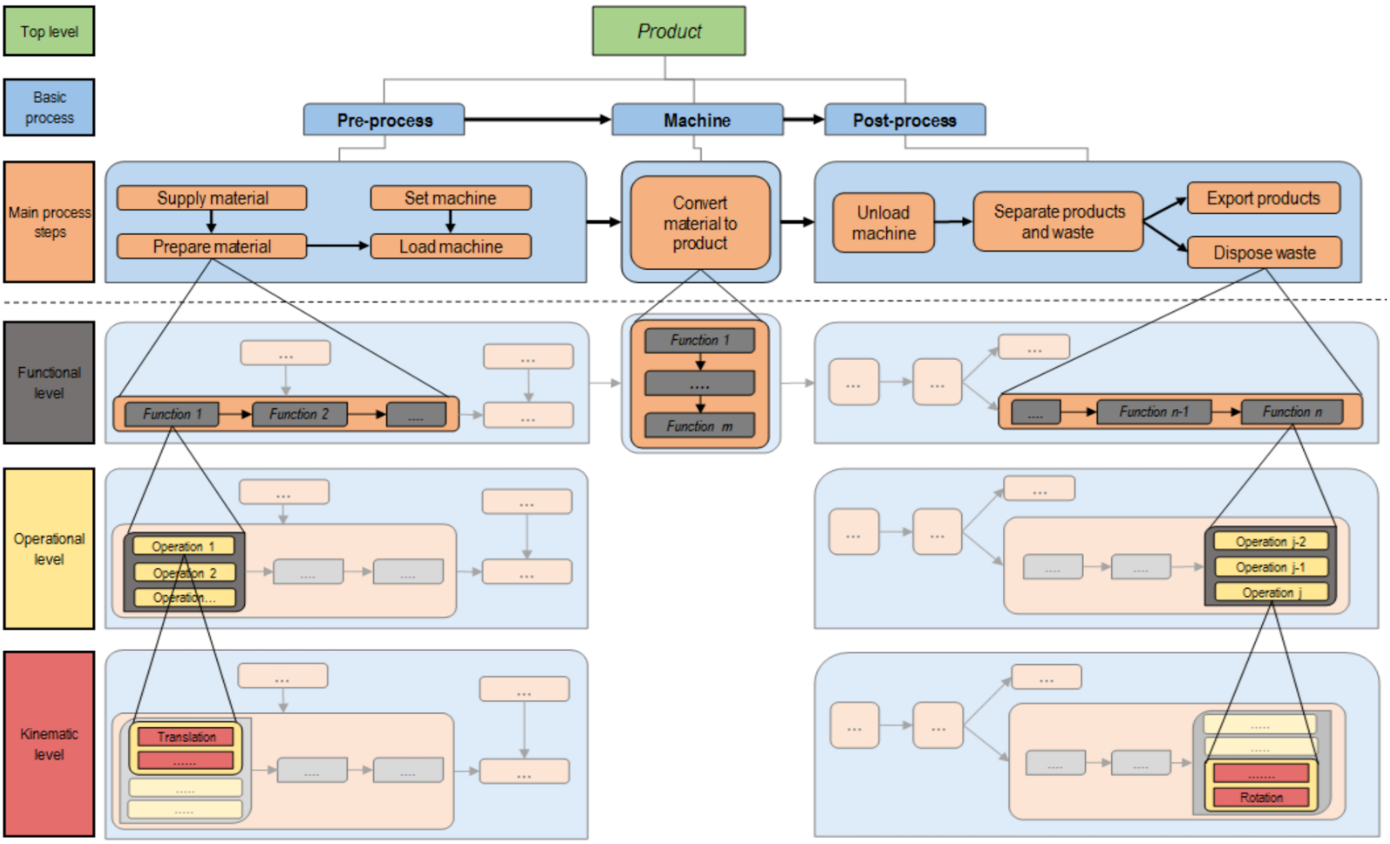

Figure 4 Process decomposition

4.4. Iterative automatization process

After analyzing both the product and the process, the third phase of the design method is the iterative automatization process. The motivation behind the iterative automatization process is to reduce the complexity of the steps of the production process to achieve a state in which off-the-shelve automatization solutions (e.g. sensors, handling) can be used to solve a generalizable problem. This is in contrast to company-specific problems that are hard, or expensive to solve or require tailor-made automatization solutions. The iterative automatization process is envisioned to be supported by a database in the making that contains existing automatization solutions, their applicability, and the pros and cons. Comparable to DFMA, the iterative automatization process intends to recognize opportunities for reducing the complexity of assembly and manufacturing, except with high variety of products and increased automatization in mind.

4.5. Design Output

The last phase of the design method is a coming together of product and process. On the one hand, based on the previously established functional requirements of the product and its design space, the tolerated adjustments to the product are known. On the other hand, based on the production process analysis and the iterative automatization process, insight is provided in the available resources and standardized solutions.

5. Conclusion

This paper proposes a design method to improve decision making for cost-effectively realizing high variety products. Throughout this paper, the term ‘high variety products’ is used to describe products that contain at least one product part with a customized geometry. The practical relevance of this study is demonstrated by describing three cases from the industry. Some of the examined companies already manufacture high variety products but are challenged by increasing the level of automation of their assembly process, whereas others are more advanced in automation but encounter complications in reducing their series sizes and in adding geometrical variety to their product portfolio. Two core findings of this research on high variety products include the following. First, the achievable product variability of a production process depends on its weakest link (i.e. the process step least robust to geometrical variation). Hence, the need for analyzing the complete production process, and consequently a process decomposition of process steps, is included in the design method. Second, the design freedom of a product (i.e. the adjustability of product design) is regarded as an enabler for customization and increased automatization of the production process. Hereby, investigating and defining this design freedom is deemed essential for the design method. Future research will include the development of optimized redesigns for the products to improve that product for later product development stages; and the evaluation of the effects of these product modifications against benefits in the production automation stages.

6. Project Next UPPS

This research is part of Next Ultra-Personalized Products and Services (Next UPPS), a research project granted by the Dutch Research Council (NWO). Next UPPS is a collaboration between the three Dutch universities TU Delft, TU Eindhoven, and the University of Twente, and six partners from the industry. The research focus of the University of Twente is aimed at cost-effectively manufacturing small lot sizes of high variety products, with personalized products in lot-sizes of one as the ultimate goal. The research foci of the other researchers involved in the UPPS project target capturing customer needs and translating customer needs into design parameters.

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