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Product personalization enabled by assembly architecture and cyber physical systems

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A B S T R A C T

Personalization is an emerging manufacturing paradigm towards meeting diversified customer needs. This paper proposes a framework for producing personalized products efficiently. An approach for optimal mix of different module types is proposed in order to construct a proper assembly architecture. Sketch-based modeling, which facilitates easy model creation and modification by customers, is presented as a key to personalized design. A cyber physical system provides the platform for the collaborative design and co-creation of personalized products. A case study on personalized bicycles based on the proposed framework is presented. Such a framework enables open product realization through active customer participation.

1. Introduction

Several paradigms have emerged in the history of manufacturing, such as mass production and mass customization [1–3]. Each paradigm is associated with different consumer driven market dynamics and enabled by the technologies of the time. Fig. 1 provides a summary of the evolving paradigms and the enabling technologies of each industrial era. It can be observed that the emergence of a new manufacturing paradigm was always accompanied by new technological advances. For example, the invention of electrical power led to the wide use of dedicated machines and automated production systems for mass production. CAD/CAM and flexible automation systems made mass customization possible.

Today, we are at the cusp of a new industrial revolution [4]. Smart machines, people, and enterprises connected by the high speed internet will fundamentally change manufacturing. Such connected systems, called cyber physical systems (CPS) [5], will improve manufacturing quality and productivity by supporting smart manufacturing. More importantly, CPS will fundamentally transform manufacturing by enabling customer participation in product realization and supporting the collaboration of customers, suppliers and manufacturers. Personalization is emerging as a new manufacturing paradigm aiming to address the highly diversified customer needs and the strong customer desire to participate in product design and manufacturing [1,3].

	Mass Production	Mass Customization	Personalization
Enabling Technologies	Mechanical and Electrical Power	CAD/CAM, Flexible Automation	Cyber Physical Systems
Production Goal	Scale	Scale Scope	Scale Scope Value
Customer Role	Buy	Choose Buy	Design Choose Buy

Fig. 1. Manufacturing paradigms supported by enabling technologies. (Adapted from Ref. [3]).

To realize personalization, several challenges need to be addressed by developing the following key enablers [3].

Open product architecture: Personalized products will have a modular architecture allowing the integration of user designed modules together with other manufacturer designed modules [1,6]. Extensive work has been done in relevant areas, such as research on platform-based product development, product line design, and product portfolio planning [7]. However, since most existing methods deal with product architectures by considering only common and customized modules for mass customization, these methods have not been applied to product architectures with additional personalized modules. In addition, effective interface management will be a key issue to achieve compatibility of personalized modules with high design variations.

Personalization design: Customers will participate in the design of personalized modules and assemblies as amateur designers. Since available design tools and systems are for trained professional designers, new methods and interfaces need to be developed to support these amateurs in design. These methods can guide the design by customers, facilitate easy model creation and modification, and ensure close collaborations between customers and expert designers are possible [1].

Responsive CPS: CPS will support the collaboration and data sharing in distributed design and on-demand manufacturing. Cyber-enabled design tools and interfaces are essential for helping to manage the high level of freedom-of-expression while satisfying

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engineering constraints [5]. For highly varied personalized designs, new user-in-the-loop simulation tools are desired for product validation in terms of efficacy, safety, and manufacturability. Additive manufacturing (AM) technologies enable responsive realization of personalized modules with the capability of fabricating 3D objects directly from CAD models [8]. Computational tools for AM process planning are imperative for on-demand manufacturing of personalized modules.

This paper proposes new methods and tools to address these challenges, including optimization of assembly architecture, personalization design tools, and CPS for personalization. Then an integrated framework is presented for personalized production and demonstrated with a personalized bicycle case study.

2. Open assembly architecture and module differentiation

Modular architectures allow for economy of scale at the component level. Hu et al. [1] proposed an open assembly architecture consisting of common, customized and personalized modules for personalized products. Here, a major challenge is to mix the module types within a single product to satisfy customers economically. The selection of customized module variants was usually formulated as an integer programming problem for profit, share of choice, or welfare [6,9]. Personalization, however, will introduce additional complexity since the manufacturer must determine the degree of personalization offered in a given module. Berry et al. [10] developed an optimization method to determine the discrete choice of module variants and a continuous personalization parameter simultaneously. However, this method did not consider situations where the assembly architecture may involve the selection and combination of multiple attributes for a personalized module, and the complication in characterizing the intricate relationships among product functionality, cost, and specificity. Another challenge stems from interface management to accommodate design variations of personalized modules.

2.1. Optimal mix of product module types

The mix of product module types can be expressed as a hierarchical decision making process in Fig. 2. Assume a product platform consisting of m modules, where $m = 1, \ldots, M$, and each module includes l candidate variants, where $l = 1, \ldots, L_m$. Each module variant is either a non-personalized variant or a personalized variant. A module can have multiple non-personalized variants but only one personalized variant. The goal is to determine the choice-menu of module variants as well as the key parameters of personalized modules from which customers can derive their products through assembly combination of variants. Manufacturer determines the module variants offered to s market segments, where $s = 1, \ldots, S$, and x_{sml} is a binary variable whose value equals 1 when selected and 0 otherwise.

A module will be offered as either a common module with one non-personalized variant, a customized module with multiple non-personalized variants, or personalized modules with one personalized variant. Further decisions are necessary for any personalized modules. For example, a personalized bicycle may offer a handlebar with two personalized attributes: shape-tailored grips and customer-designed bar. The manufacturer should decide how to mix these attributes with economical parameters. In Fig. 2,

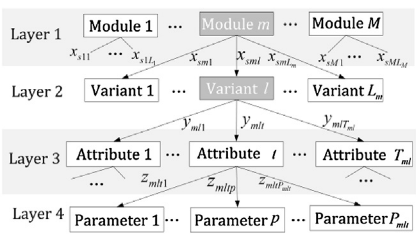

Fig. 2. Hierarchical decision making process.

suppose variant l is a personalized variant with p personalized attributes, where $p = 1, \ldots, P_{mlt}$. Here the choice for each personalized attribute y_{mlt} s described as a binary variable

Attribute parameters describe the key design and manufacturing parameters (e.g., process, material, accuracy) dominating product functionality and manufacturability, and variable z_{mltp} represents the parameter value.

The optimal assembly architecture is achieved through the tradeoff between the utility and the manufacturing cost. The manufacturer will propose an initial product portfolio with all candidate module variants. For a non-personalized variant, the utility is determined by market research and conjoint analysis. Utility function $u(e)$ will be fitted to module utility against functionality. Manufacturing cost will include variable unit cost c (related to material, labor, and operations), and fixed unit cost f (related to manufacturing system utilization). Manufacturers should determine the cost of each module variant during process development. Functionality e will be determined from knowledge or data in pilot experiments. For personalized module variants, the evaluations of utility, variable cost and functionality depend on the attribute combination and parameter values to offer. A metric called *personalization quotient* (PQ) is introduced to characterize the personalization degree of a module,

$$\xi(\mathbf{Y},\mathbf{Z}) = \sum_{t=1}^{T_{ml}} y_{mlt} w_{mlt} \sqrt{\sum_{p=1}^{P_{mlt}} r_{mltp}^2 (z_{mltp}) / P_{mlt}} \tag{1}$$

Here, w_{mlt} weighs the impact of attribute t on the achievement of personalization. Variable r_{mltp} represents the personalization degree of parameter p. For a continuous attribute parameter p (e.g., manufacturing error), PQ is calculated by Eq. (2).

$$r_{mltp}(z_{mltp}) = \left(z_{mltp}^{+} - z_{mltp}\right) / \left(z_{mltp}^{+} - z_{mltp}^{-}\right) \tag{2}$$

where variable z_{mltp} represents the parameter value, with z_{mltp}^{-} and z_{mltp}^{+} being its lower and upper bounds, respectively. For a discrete parameter p, r_{mltp} will be evaluated according to its performance in function fulfilment. Extensive ergonomic or psychological experiments are usually needed to formulate the functionality function $e(\xi)$. The cost function will be denoted as

$$c = (\mathbf{Y},\mathbf{Z}) = \sum_{t=1}^{T_{ml}} y_{mlt} f(Z_{mlt}) \tag{3}$$

Here, $\mathbf{Z}_{mlt}$ is the parameter vector of attribute t, and $f(\mathbf{Z}_{mlt})$ is the cost function. Mathematically, the optimal mix of product module types is then formulated as a welfare problem with the following objective function,

$$max\left[\sum_{s=1}^{S} \sum_{m=1}^{M} \sum_{l=1}^{L_m} q_s (u_{sml} - c_{ml} - f_{ml}) x_{sml}\right] \tag{4}$$

subject to the following constraints,

$$\sum_{l=1}^{L_m} x_{sml} = 1, x_{sml} = 0 \text{ or } 1, \forall s, m \tag{5.1}$$

$$\sum_{t=1}^{T_{ml}} y_{mlt} \geq 1, y_{mlt} = 0 \text{ or } 1, \forall m, l \tag{5.2}$$

$$z_{mltp}^{-} \leq z_{mltp} \leq z_{mltp}^{+} \text{ for continuous } z_{mltp}, \ \forall m, \ l, \ t, \ p \tag{5.3}$$

$$z_{mltp} \in \{1, \ldots, N_p\} \text{ for discrete } z_{mltp}, \ \forall \text{m}, \ l, \ t, \ p \tag{5.4}$$

Here, u_{sml}, c_{ml}, and f_{ml} are constants for a non-personalized module. Otherwise, they will be evaluated by $u(e)$, $e(\xi)$, $\boldsymbol{\xi}(\mathbf{Y},\mathbf{Z})$, and $\mathbf{c}(\mathbf{Y},\mathbf{Z})$ jointly.

2.2. Interface management

Interface standardization is important for achieving module compatibility [11,12]. The modules of an open-architecture product should have standard mechanical, electrical and informational interfaces, which define the protocol of the module interactions to perform the designated functions. Particularly, this paper will discuss the mechanical interfaces, which can be described as the