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A review of mass customization across marketing, engineering and distribution domains toward development of a process framework

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Abstract Introduced nearly 25 years ago, the paradigm of mass customization (MC) has largely not lived up to its promise. Despite great strides in information technology, engineering design practice and manufacturing production, the necessary process innovations that can produce products and systems with sufficient customization and economic efficiency have yet to be found in wide application. In this paper, the state-of-the-art in MC is explored in the context of an envisioned MC development process for both the firm and the customer. Specifically, 130 references are reviewed within the process frameworks (Sect. 3) and/or to highlight opportunities for future development in MC (Sect. 4) based on the review. This review yields opportunities in four primary areas that challenge MC development: (1) customer needs and preference assessment tools, (2) approaches for requirement specification and conceptual design, (3) insights from methodologies focused on the development of durable MC goods and (4) enhancements in information mapping and handling.

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1 Introduction and motivation

The concept of mass customization (MC) was put forth by Davis (1987) nearly 25 years ago. Yet, despite great strides in information technology, engineering design practice and manufacturing production—all components necessary to make the paradigm realizable—MC has largely not lived up to its promise. There are a few examples of successful mass customization implementations (e.g., Dell offers customization of their computers), but these are largely limited to systems where the existing, dominant product architecture enables MC to be viable. Some of these MC offerings also only occur at higher price points [e.g., Trek's Project One starts at $6,500 dollars (Trek Bicycle Corporation 2013)]. It is possible to find more examples of MC when looking at service industries (e.g., web services) and textiles or clothing. However, when looking toward durable goods (e.g., automotive, consumer appliances), it is difficult to find wide spread application of MC. It is from this perspective of durable good development that we approach this investigation.

In an article by Zipkin (1997) regarding limitations of MC, the paradigm is considered more "buzz" than viable product development model. This perspective is an important one as the reality is that MC is not likely to work for every company for varied reasons. Zipkin points to a few key challenges, including (1) difficulty in eliciting individual needs and preferences from consumers that lead to meaningful customization, (2) elicitation methods and configuration mechanisms that support customization without overwhelming the consumer with options, (3) production methods and knowledge flexible enough to provide customization on multiple attributes and dimensions, and (4) producing and delivering products for an individual in a mass production facility.

The fundamental interest in this research is to understand why the paradigm has stalled; is it just "buzz," as Zipkin implies, or are there fundamental aspects of the MC product development model that are not addressed by the current research? Increased global competition from the emerging economies in developing nations, and the increasingly fickle consumer looking for variation and individualized products, had led many researchers and companies to agree that an economic motivation for MC exists (Gilmore and Pine 2000). However, the necessary process innovations that can produce products and systems with sufficient customization and economic efficiency to match these market drivers have yet to be found in wide application. In this paper, the state-of-the-art in MC is explored in order to identify where opportunities in the paradigm exist.

In utilizing the term "mass customization," it is critical to provide a basis for what that term means in the context of this paper. Semantically, the concept of MC is a method to provide consumers with custom goods (and services) at prices consistent with mass production. As defined by Davis (1987), MC is a paradigm that would provide consumers "exactly what they want when they want it." This view of MC sounds like a Star Trek "replicator" and is an extreme view that current technology could not produce. However, the spirit of the Davis definition is that the form and function of products should be in exact accordance with the needs and preferences of each individual.

For this paper, the type of MC that we are interested in is in line with the spirit of Davis' definition. As such, the definition setting the context and perspective for this research is that MC is *a product development approach that allows for the creation of goods that minimize the trade-off between the ideal product and the available product by fulfilling the needs and preferences of individuals functionally, emotionally and anthropometrically, while maintaining system costs comparable to mass produced products.* This definition also agrees with that of Piller (2004), who suggest that there are three types of customization: style (emotional), fit and comfort (anthropometric) and performance (functional).

Another critical element of discussion, again in agreement with Piller (2004), is that MC is defined by a fixed solution space. This is different than traditional craft customization, which has a theoretically unlimited number of solutions. It is recognized that for MC to be economically viable today, a finite solution space is a fundamental assumption—at least until the replicator becomes a reality.

Finally, the view of MC taken here has one other key parameter; the product is not fabricated until the customer places an order. For example, this definition eliminates a predefined product family, but allows for platform-based customization. Ordering a Dell computer is an example of MC—one which relies on modularity. On the other hand, purchasing a car with a particular option package is not MC—even though the consumer may need to wait for the car to be delivered. This final qualification for MC ensures that MC must rely on strategies, practices and technologies like "build-to-order," "assemble-to-order," modularity, reconfigurability/flexibility, agile/flexible manufacturing and rapid prototyping (3D printing, CNC) in customizing and delivering the final good.

These three parameters of MC in application create a basis for developing a product development framework to support rigorous design decision making during the product development process. Specifically, the need to minimize the trade-off between ideal and available product for *each* customer coupled with a fixed solution space implies the need to create a multi-space model of product preference, representing consumer choice parameters that is connected to the technical parameters over which designers make decisions.

This paper supports the belief that MC is a realizable paradigm for the design and delivery of many products and systems, which must satisfy heterogeneous markets and market segments. It has the potential to emerge as one of the dominant design paradigms. Yet, the expansion of the MC paradigm is dependent on developing rigorous models and tools that support designers throughout the MC product development process. This will be critical to overcoming the challenges highlighted by Zipkin, which any company considering MC would have to work through.

This paper presents a review of literature related to mass customization, which is presented in the context of a proposed MC product development framework. The framework is introduced and described in Sect. 3. Section 4 provides conclusions and suggestions for future work critical to operationalizing the proposed framework in a way that leverages the MC research developments in recent years. The following section details the approach followed in our review.

2 Literature review methodology

The methodology used in this research is a review of the literature since 2000. This can be a daunting task as the term "mass customization" returns plenty of results in most search engines whether they are internet-wide (e.g., Google) or journal database specific. For example, a search for the term "mass customization" in Google returns 747,000 results for the web and 29,200 results in Google Scholar (as of May 2013). Similarly, searching databases of archived journals like ScienceDirect and the ISI Web of Knowledge return 1,039 and 740 results, respectively.

Given the ubiquitous existence of the MC topic, a specific framework to guide the search for literature on MC was devised. That framework considers the detailed stages of the design process broadly divided into three categories—marketing, engineering and distribution. While these broad categorizations could be applied to traditional products, these categories align well with the development and delivery of mass-customized products in practice. That is, for a company to master MC, they must be proficient in: (1) understanding individual needs (marketing); (2) developing products/systems robust enough to adapt to consumer differences (engineering); and (3) managing supply chains to support flexible manufacturing and/or assembly and timely delivery of final customized goods (distribution).

Based on this framework, a literature search spanning these categories was conducted using a number of journals. Papers were identified by searching each journal for the terms "customization" or "mass customization." The results returned were then skimmed briefly, or their abstracts reviewed, to ensure that the content of the paper indeed had some relation, directly or indirectly, to MC. Targeted journals were selected based on our familiarity with them as good sources of design-related information that could be aligned with the three domains (marketing, engineering, distribution); we expected to find state-of-the-art information on the topic of MC. Specific journals targeted in our search that represent significant sources of references include AI EDAM (8 papers), Concurrent Engineering (13), Expert Systems with Applications (12), International Journal of Computer Integrated Manufacturing (11), International Journal of Production Economics (12), Journal of Consumer Marketing (3), Journal of Manufacturing Technology Management (4), Journal of Marketing Research (2), Journal of Intelligent Manufacturing (10) and Journal of Product Innovation Management (4). Additional papers that fell outside of these primary resources were also included, as suggested by colleagues and reviewers, from sources like Journal of Engineering Design, International Journal of Mass Customization and Research in Engineering Design.

In total, 130 papers specific to MC (or closely related topics) are reviewed; however, it is not suggested that this review of the literature is exhaustive. Rather, it is representative of work important to the MC domain, which can be linked to specific stages of the design process—governed by the domains of marketing, engineering and distribution—as will be detailed in Sect. 3. It is also worth pointing out that this review works as a complement to a recent MC review by Fogliatto et al. (2012) which overlaps on some references.

To bring a level of formalism to the review and encourage consistency across the review team, six questions were developed. These questions are general in that they could, for the most part, be applied across the categories to all the papers reviewed. It is not the goal to review each paper with respect to these questions, but the questions did aid in drawing out specific findings that can be related to the design process for MC in general. These questions are the following:

1. Is the methodology described in the paper intended to support MC directly? If not, does the methodology described have clear implications for MC?
2. Does the paper focus on quantifying the effects of implementing a MC methodology?
3. Does the paper describe specific information inputs for the methodology? What is the source of the information (e.g., consumer or engineer)?
4. Does the paper describe specific information outputs for the methodology? What is this information used for?
5. Are there any MC specific metrics described in the paper? Are equations used to represent these metrics? How useful are these metrics?
6. Are there significant barriers to implementation of the MC method presented? What are they?

The purpose of question one and two is to establish the fundamental motivation of the work being reviewed. In the case of question one, research results provide specific approaches to supporting MC across the three domains of interest (marketing, engineering and distribution). Literature motivated by question two, on the other hand, is likely to provide evidence regarding the effects (positive or negative) of implementing MC across a particular industry, identify best practice for MC techniques and/or provide paths for further research efforts by identifying specific challenges in MC (e.g., the role of the consumer perspective of MC).

Question three is rooted in a desire to understand the form and origin of information that serves as an input to a specific methodology. The interest is to understand how information requirements for MC approaches might differ from other design methods and to see how information varies across the design domains. Question four is a complement to question three and is focused on understanding how information outputs from various MC methods differ from traditional design methods and across the three design domains. It is important to understand information inputs and outputs because the alignment of such information flows is critical to execution of a successful MC design process, especially where inter-domain flows are likely or necessary.

Question five looks to document any metrics that have been developed through MC research. Metrics should be critical drivers that facilitate operationalizing the MC paradigm. Documenting metrics and understanding how they relate to various information inputs/outputs is of particular interest in this work.

Finally, question six works to quantify barriers that might impact the ability to implement a specific methodology or the MC paradigm as a whole. These barriers could be identified by the authors of the reviewed works or may be barriers identified by the authors of this paper. This type of information is critical to understand critical challenges that must be overcome and identify future areas of research.

Answering these questions during the review of each paper was intended to provide insights into the additional complexity that MC brings to the product development process. A working assumption at the beginning of the review was that these papers would highlight the need for methods capable of bridging aspects of the development process beyond—and in addition to—current advances in IT, design practice and manufacturing capability. That is, an effective MC design process requires an intimacy between aspects of the development process that is not currently *necessary* in traditional product development if economies of scale are to be maintained despite lower minimum production quantities, as suggested by Bardakci and Whitelock (2003). For example, the use of four objectives by Yao and Liu (2009) that draw on information from within the firm and from the consumer signifies the additional types of information that must be collected and processed to support MC production decisions. These objectives describe the economic parameters and preferences (utilities) that constitute the key contradictions between consumer satisfaction and economies of scale. Reviewing the paper in this context highlights the need for tools and approaches capable of coordinating the different disciplines and processing the large quantities of information that is created because of increased domain interaction.

Additionally, increased customer integration into the design process is an inherent consequence of the MC definition provided in Sect. 1. Furthering domain coalescence and increasing inclusion of the customer require some rethinking of the product development framework to support incorporation of domain-specific techniques for mass customization. The next section describes the framework for such a process.

3 Proposed framework for mass customization

For MC product development to be a successful paradigm, the level of domain autonomy found in current product development cycles needs to be reduced further. Therefore, it is important to consider advances in MC techniques in the context of the design process, which might lead to identification of the most appropriate "mode" for delivering MC goods (MacCarthy et al. 2003). Figure 1 represents a product development framework proposed as an idealized approach to support MC product design and delivery, which reduces that autonomy. This framework is a conceptualization of the authors; however, it is influenced by the review of literature covered in this paper. The framework serves as context for specific review of the literature. To support mapping and discussion, each design task is described here. Existing research is then reviewed in the context of this process.

The staged structure of the process shown in Fig. 1 (e.g., Product Planning… Requirement Specification…) is similar to sources like (Ulrich and Eppinger 2000) as a basic representation of the product development process. These high-level stages occur whether the product being developed is mass produced or MC in nature. However, the required tasks in each stage differ based on the amount of product variety being offered by the design firm. These stages are traditionally associated with the marketing (*M*), engineering (*E*) and distribution domains (*D*) as previously defined, and represented in the Venn diagram as red, blue and yellow, respectively. The detailed development activities associated with each stage are color-coded to represent ownership by a specific domain (i.e., the domain primarily responsible for completion of the task). The intersections of one or more domains—purple for ME, orange for MD, green for ED and gray for MED—signify places where the traditional domains must work more intimately to exchange information and generate knowledge in support of MC products; in these cases, ownership is shared by multiple domains. The following sections elaborate on each stage and review the related MC literature in the context of those stages.

3.1 Product planning

3.1.1 *Customer needs identification*

This first step represents basic identification of needs common to any product design. However, "tuning" the need identification process across potential MC customers is critical, perhaps more critical than the technology development stages that typically dominate design for product variety. In support of this notion, the literature review from Fogliatto et al. (2012) points to several

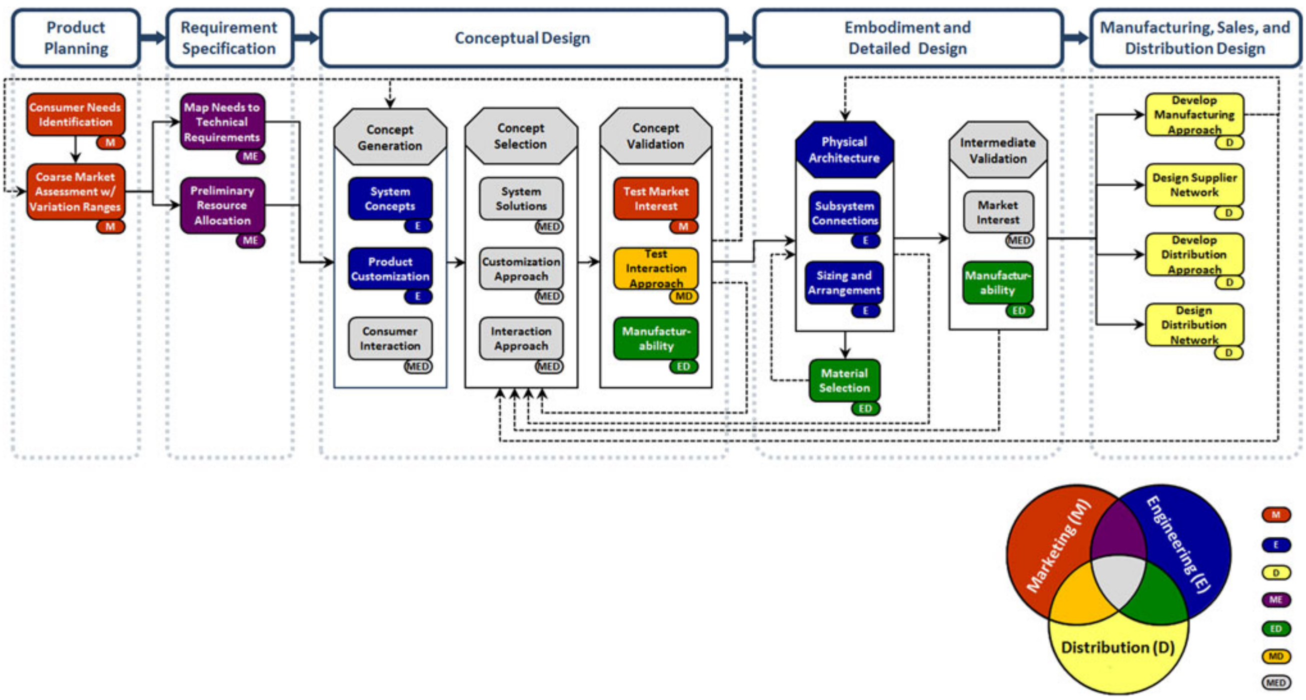

Fig. 1 Proposed process framework for mass customization with domain interaction

studies from Salvador et al. (2009), Bardakci and Whitelock (2003), Jiang et al. (2006), Kaplan and Haenlein (2006), McIntosh et al. (2010) as evidence that a focus on consumer needs and preferences is more important than a focus on a particular technology or product mix. Further, the review conducted by Zhou et al. (2012) suggests that MC may be better supported by affective and cognitive need elicitation in an effort to identify latent needs.

3.1.2 *Coarse market assessment with variation ranges*

After initially identifying customer needs, a course market assessment is required to identify what differentiates possible customers and the regions of the market that are economically attractive. Further, understanding the variation ranges associated with specific needs and their relation to other customer variables like demographic and anthropometric parameters is important. This stage goes toward establishing a basis for the development of a flexible product architecture capable of supporting mass customization.

Handling both of these activities as part of the Product Planning stage for mass customizable products brings forth three key questions that have been explored in the literature and must be answered pragmatically by firms. Namely, Who wants customization? What do they want to customize? Are they willing to pay additional costs (cognitive and economic)?

As a starting point for coarse assessment, Bardakci and Whitelock (2003) include as a critical assumption that market niches are too broad to satisfy (i.e., heterogeneity is significant even within traditional segments) with product variability alone. However, even within these fragments, identifying the customers who *want* customization is critical considering their influence on the customizable architecture. That is, “customization psychology” must be understood (Bardakci and Whitelock 2003; Guilabert and Donthu 2006). It cannot be assumed that interest will span traditional market segments uniformly (or that this would make economic sense if it does). Specifically, they put forth a model for establishing “customer readiness for MC” by testing three hypotheses: (1) customers are willing to pay a premium for customization; (2) customers are willing to wait a reasonable period to receive their customized product; (3) customers are willing to spend a reasonable period of time to specify preferences when ordering customized products (at least on first occasion). The resulting decision framework for testing these hypotheses would be useful at this point in the process.

Piller (2004) found that people are either very interested or not at all interested in customization, with very little opinion in the middle (based on 7-point Likert scale for a shoe customization case study). Further, they found gender and culture to be important factors. In their particular case study, they conclude there is opportunity to be successful with customization, but that coarse market assessment is important.

These papers highlight that developing methods for finding "potential customizers" is a critical first step that must be integrated with the general design process of Fig. 2. In the literature, these techniques can vary from the simple to the complex. For instance, the tools used by Piller (2004) are not sophisticated (traditional surveys and focus groups), yet led to high-resolution insights (e.g., customization in Italy is less desirable because there is significant variety in footwear as compared to other European countries). Similarly, Guilabert and Donthu (2006) propose a mechanism for assessing customization interest on the part of individuals via survey. The proposed Customer Customization Sensitivity has five levels, which can be used to examine how consumers feel about customization, specifically whether they might be pleased with it or confused by it.

More sophisticated techniques aimed at identifying customers interested in customization include (Kaplan et al. 2007), who explore factors related to the "base category" of a product (i.e., all standardized products within the same product category as the mass-customized product being considered). Specifically, they explore the role of satisfaction, and frequency of interaction, on the interest in customization. They find that there is a significant direct positive influence from base category consumption frequency and need satisfaction to the intent of adopting a mass-customized product. The more often subjects consume products out of the base category, or the more satisfied their needs are due to this consumption, the more likely they are to be interested in a related customizable good.

While the work of Kaplan et al. (2007) is not focused on developing a methodology (and is potentially limited, as the authors admit, given the test case being newspapers), their findings provide support for developing methods based on tracking frequency and consumption satisfaction of base category products. In fact, there are a number of advancing tools in the realm of business/web analytics that look to capture this type of information. For example, using known purchase history data with customer review data (as well as geographic and customer profile data) represents a basis for coarse assessment of potential customers interested in customization (Liao et al. 2009; Li et al. 2013).

Hypothetically, continued advancement of web-based shopping combined with evolving analytics could lead to direct identification of customers interested in customization. Though, Pitta et al. (2003) discuss the importance of understanding the tradeoff between using advanced information technology to gather idiosyncratic customer information and the issue of customer privacy. Failure to

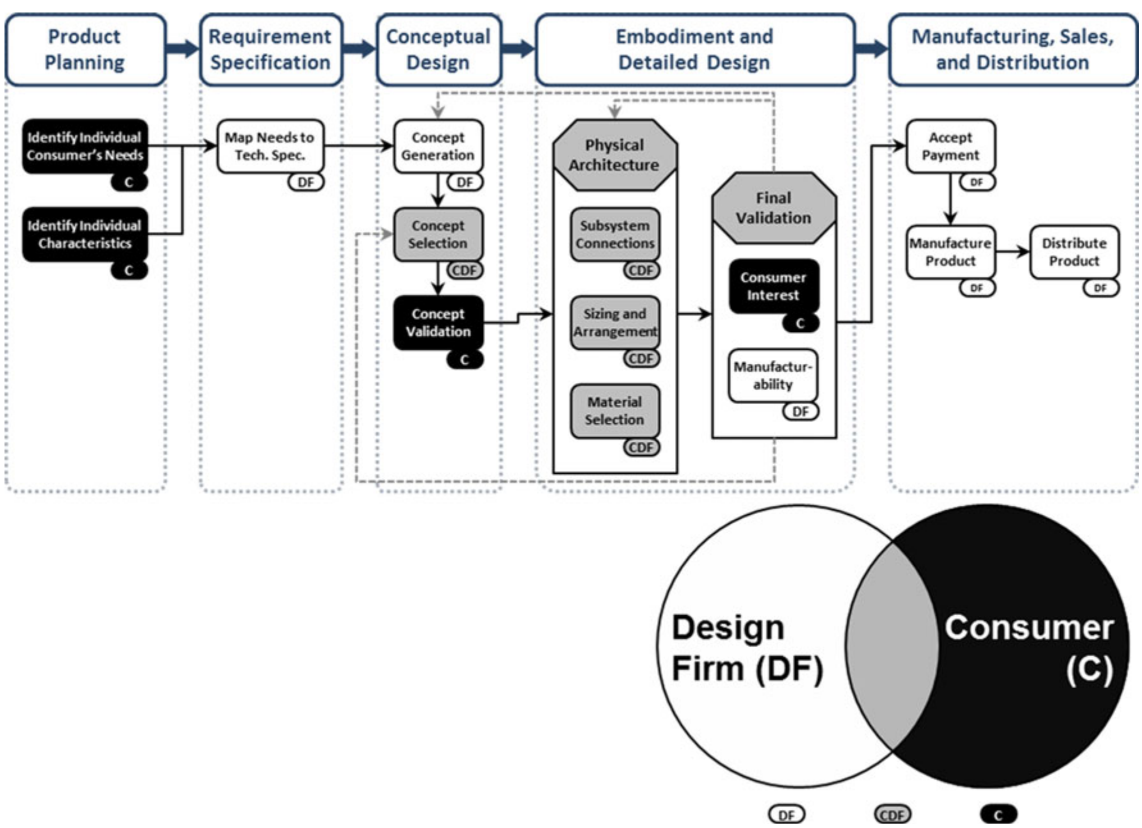

Fig. 2 Individual consumer design process

consider such privacy concerns has the potential to limit the development of customer relationships that are critical to the customization process.

Assuming a firm is capable of identifying the right customers, the next challenge is determining the product features that consumers want to customize. This many-to-many (customers-to-features) mapping complicates the problem beyond the already difficult challenge of determining appropriate product variety in standard mass production offerings. Arguably, the challenge of understanding customization preferences can benefit from existing methods like discrete choice theory. In recent work, Ferguson et al. (2011) explored the use of discrete choice approaches as a basis for segmenting markets in support of customization. Liechty et al. (2001) introduce a Bayesian-based approach, MVP (multivariate probit model), intended to improve understanding of menu-driven product customization. Of particular interest is consideration of menu options that accommodate constraints arising from feature incompatibility. Their method is demonstrated as being better at predicting a preferred portfolio of options over traditional menu-based conjoint methods. Fogliatto and da Silveira (2008) propose and test a method for determining the optimal choice menu design using consumer segments by leveraging traditional market research methods (focus groups, surveys), cluster analysis and experimental design techniques; stated preference models and logistic regression are used to create the segments. Their view is that using the choice menu approach is one effective way to gather preference data. The method faces the challenge of balancing insufficient and too much choice.

Methods that deviate from a discrete choice basis are also likely to be important, especially as appropriate customizable product solutions may be highly sensitive to idiosyncrasies that vary by culture, geography, other demographic information (Piller 2004) and highly subjective factors like "style." Fung et al. (2004) focus on understanding "styling" (i.e., esthetics of product form) and the relationship to fashion trends. The importance of this work relates to the difficulty in assessing something as amorphous and subjective as "style," which is often represented by product form. In proposing a model for style preferences, the authors are looking forward in the process to the establishment of appropriate product platforms and modules and the potential for fashion trends (i.e., a critical mass of consumers preferring particular styles) to enable production efficiencies more in line with mass production. Similarly, Jiao et al. (2006), Zhou et al. (2012) consider "affective responses" (psychological understanding of consumer perception) to design elements, proposing a specific methodology for capturing such information and mapping it to design parameters. Chen et al. (2003) propose an approach for acquiring and evaluating multicultural factors based on laddering and a radial basis function neural network. Their paper demonstrates the potential for neural networks to provide a powerful and fast method for uncovering the distribution pattern for customer requirements evaluation.

Finally, once interested customers are identified and preferences quantified—even at the coarse level desired here—there is still a need to understand the economic and cognitive cost limits associated with the customer customizing the good. Piller and Müller (2004) cast this as the premium of the individualized product compared to standard offerings and the cost of actively participating in the design of the product. Piller (2004) explores this in terms of utility versus cost, where utility is a function of the improved product through customization *and* value of the co-design experience. Cost is a function of price premium for individualization and the cognitive/time cost required for configuration. Dellaert and Stremersch (2005) address this similarly, looking at the tradeoff between increased utility due to customization and decreased product utility associated with customization complexity.

While the basic functions of this development stage are similar to standard design practice, the MC literature demonstrates increased complexity associated with the desire to create a customizable good. Further, these factors are not mutually exclusive. Notably, customers interested in customization are sure to vary, not only in preferences for what features to customize and levels of customization, but also in their cognitive and economic limits. If these economic and cognitive limits are exceeded, a well-designed product (from a feature customization perspective) will not be purchased. This is analogous to purchase price and "ease of use" constraints for mass-produced goods, but in the customization case, the economic and cognitive costs are a new dimension in that firms must now also design the customization system itself.

3.2 Requirement specification

3.2.1 *Preliminary resource allocation*

This step represents an initial allocation of human and economic resources based upon the coarse market assessment, engineering requirements and company objectives. In an MC product development circumstance, resources are also necessary to design the customization system that involves the customer (as discussed in the subsequent section).

3.2.2 *Map needs to technical requirements*

Based on information developed through product planning, engineering specifications (metrics and *range* of values) must be identified and established. This is similar to standard product development, though solutions that accommodate the range of values desired are met through custom goods rather than different fixed product line offerings. This presents a need to identify "consumer clusters" that includes correlation between engineering specifications and needs and high-resolution demographic and anthropometric parameters.

Existing work by Zha et al. (2004) proposes a method for determining product variants based on the voice of the customer, with a product family being viewed as a means of offering MC. This approach leverages market trends and customer requirements to identify the product variants and their respective composition. This work essentially automates the process of generating technical requirements, but does so without direct customer involvement. While this may be appropriate for certain markets and consumers, it does not capture the degree of consumer involvement or the level of customization envisioned by Davis (1987). Olewnik and Hariharan (2010) developed an evolved QFD-based approach that integrates discrete choice theory in an attempt to let consumers directly drive identification of the importance of engineering requirements, but the methodology requires a significant level of interaction with potential consumers if it is executed as envisioned.

Work in this area specific to MC has looked at optimizing the overall product family while satisfying the performance constraints of the variants (Gonzalez-Zugasti et al. 2000). The same research group went on to use value analysis under uncertainty to select platform variants and levels (Gonzalez-Zugasti et al. 2001). Both of these approaches are essentially setting technical specifications for the product variants; thus, the method assumes a product platform approach is being used.

Though our literature search is not exhaustive, it is apparent that there is a lack of research focused on the development of technical requirements for MC products. The literature identified here is limited, fundamentally, by the assumption of MC being driven by product families. Though it may turn out that product families are a predominant mechanism to achieve MC, it is undesirable to assume a particular solution mechanism prior to the conceptual design phase as this may artificially constrain the potential solution space.

3.3 Conceptual design

3.3.1 Concept generation

In the framework of Fig. 1, *Concept Generation* involves three distinct activities: *System Concept, Product Customization* and *Customer Interaction*. The *System Concept* activity requires identification of the overall system concept, inclusive of form, function and interaction features (information and control) capable of serving the fundamental needs of the broader market. As a separate activity, *Product Customization* focuses on generating potential approaches to support necessary form, function and interaction variations in a customizable architecture. Finally, *Customer Interaction* is focused on generating potential methods for eliciting idiosyncratic consumer data that enables customization for the concept architecture selected. This final activity represents the first instance where all three domains interact in the proposed development framework.

Well-established engineering practices focused on concept generation can be used to identify potential system concepts. In general, the process for generating these system concepts does not have to change to accommodate the MC paradigm. However, a high level of variety is desirable, because it will facilitate the two additional requirements imposed by MC, generation of concepts for product customization and consumer interaction.

Review of the literature resulted in no specific methods to support generation of concepts for enabling customization, which would support the *Product Customization* activity. It may be that current practices utilized for system concept generation can be adapted to this specific activity. However, exploring the form of that adaptation represents a potential area of investigation for firms and design researchers. Similarly, methods to identify potential concepts for *Customer Interaction* are not offered in the literature, though specific solutions in the form of "configurators" can be found and are discussed in a later section. A comment worth making here is that while current solutions might represent a starting point, or best practice in some instances, it limits the potential to identify innovative concepts necessary for MC interaction with customers. Again, this represents a potential area for research exploration.

3.3.2 Concept selection

Here, the designers must select the system constructs (*System Solutions*), customization mechanisms (*Customization Approach*) and consumer interaction approach (*Interaction Approach*) that work seamlessly; this is a nontrivial task. This is a system-of-systems problem for which current concept selection approaches may be challenged. All tasks of the selection activity are shared by the domains as a reflection of the strict interdependency among these groups when developing a MC product.

There is significant existing work focused on the subproblem of selecting system solutions. However, the literature review revealed no approaches specific to the MC representation here, where three concepts must be selected. However, previous work might be leveraged as this problem is further explored. For example, Martin and Ishii (2002) created the Generational Variety Index (GVI) to evaluate the design effort required to add variants to a product platform. It is possible that this GVI could be adapted to help assess product customization concepts.

Adding flexibility to product platforms is proposed by Suh et al. (2007) as a method of reducing redesign costs. This approach leverages change propagation analysis as a method to help identify areas where flexibility is needed. While a design firm may not be pursuing a pure platformed approach, the idea of using change propagation analysis can be used when evaluating concepts and identifying areas of potential redesign or areas where additional customization approach concept generation is needed.

3.3.3 Concept validation

Concept Validation represents a departure from traditional mass production product development. Here, there is a need to validate the product concept derived from coarse market assessment through a *Test of Market Interest*. Specifically, the intent is to interact with potential consumers and allow them to customize hypothetical offerings and determine whether they are working in the ranges expected for customizable aspects. There is also interest in confirming that individuals have a higher perceived utility when compared to static offerings for the range of engineering requirements identified, as discussed previously.

Concurrently, *Testing of the Interaction Approach* is important to finalizing an appropriate customization interface. Consumer interaction concepts found in the literature revolve largely around web-based interfaces. In general, this research looks at the information technology required to enable these approaches. For example, Huang et al. (2007) develop an information framework that enables collaboration between the parties involved with customization. In the example provided, it does not directly involve the consumer, but the consumer could be integrated. In practice, certain companies employ other customization practices. For example, an in-store fitting is often used to address anthropomorphic variation, and is used to customize clothing, climbing packs, etc. Frutos et al. (2004) present a complete decision-support framework comprised of an object-oriented representation of the MC process intended to support the integration of consumer preferences and constraint representation for manufacturer and consumer alike. The framework assumes modular product architectures and is developed to support product configuration. Thus, while specific approaches to consumer interaction have been proposed, it is important that the mechanism be validated prior to launch as it will likely be a function of the product architecture, customization types and consumer knowledge.

Specifically, there is a need to ensure that the configurator has an appropriate combination of web-driven and live-person configurator components, behaves as expected and does not detract from the product utility. This issue relates directly to critical functions of the product planning phase and is represented by a number of studies focused on configurator design. As previously mentioned, Dellaert and Stremersch (2005) consider customer interaction aspects as it relates to the trade-off between increased utility for a customized good and decreased utility due to customization complexity. Two findings important to this framework: (1) as customers progressed in customizing a product (computers in their work), both product utility and complexity decreased (reasoning: boredom/fatigue and experience, respectively); and (2) higher product utility is achieved among consumers when default versions were presented at a base level rather than at advanced level.

Similarly, Kurniawan et al. (2006) investigate two modes of customization for a t-shirt purchasing experiment, where they vary product presentation (by attribute or alternative), shopping method (configurator or selection) and number of alternatives (16 or 256). Among a number of findings, of particular interest here is: (1) presenting by attribute increases levels of process satisfaction; (2) shopping by configurator is associated with higher process satisfaction, (3) increasing alternatives increases the benefit of the configurator; and (4) that presentation mode and shopping method are critical factors for product and process satisfaction (configurator is better for attribute presentation and selection is better for alternative). While this indicates the effectiveness by which configurators can connect with customers in MC, it further highlights the importance of a validation phase.

Finally, as part of concept validation, it is also important to consider manufacturability. Given the selected concepts, feasibility assessment and cost effectiveness (production of the core architecture and customizable features) is certainly a requirement that must occur early in the process.

As reflected by the prominence of high interaction among the design domains during conceptual design, this phase is critical to the development of a successful MC good. This stage represents an early instance in MC design where a higher level of intimacy in both interactions among the domains, and the firm and customers is important. This is explored in more detail in the conclusions and opportunities discussion of Sect. 4.

3.4 Embodiment and detailed design

3.4.1 Physical architecture

In this stage of the process, designers must determine the overall system architecture with consideration of *Subsystem*

Connections and *Sizing and Arrangement* as specific activities. Of course, the additional complication is that the architecture must now serve customization.

The broadest perspective on architecture definition to facilitate MC comes from work in product platforming (Meyer and Lehnerd 1997; Simpson et al. 2006). While heavily explored in the engineering design literature, most of the fundamental questions in product platforming have explored: (1) whether the architecture should be designed from the top-down or bottom-up, (2) if aspects of the platform should be scalable or modular and (3) how product platforming problems should be formulated and analyzed. The first formal approach found in the literature is the PPCEM introduced by Simpson et al. (2001). This method leads to a top-down architecture capable of being easily modified and upgraded through the addition, substitution and exclusions of modules. A five-step procedure characterizes this approach by describing how market segmentation grids can be used to classify desired ranges of product performance that then dictate product platform and product family creation.

Platforming the layout of subsystems was also explored by Hofer and Halman (2004) who examined the design of large, complex systems. Case study problems were primarily used to draw conclusions from this work, supporting the idea that product platforming is an effective strategy for maintaining economies of scale regardless of system size. However, an implicit assumption made in most product platforming research is that the system can be easily changed. Tools for testing the validity of this assumption come from the area of change propagation research (Eckert et al. 2004), which states that change rarely occurs in isolation and often influences other system components. As it is likely that this change cannot be avoided, the best strategy is to manage the impacts as effectively as possible. Initiated changes to product architectures are identified as those that arise from changes to customer requirements and emergent changes are identified as those that arise due to a perceived weakness in the product. Understanding the impact of a system change is done by classifying components with respect to a type of propagation: constants, absorbers, carriers and multipliers. It is suggested that by understanding where and how changes might propagate, a designer will be more effective at identifying changes to product architecture that can easily support MC.

While scalable architectures are often discussed, the literature review found few research papers that directly proposed methods for identifying scalable components or handling design challenges that may arise (Dai and Scott 2004). Rather, the literature focuses on research efforts toward handling modularity. These efforts extend from creating definitions and taxonomies (Arnheiter and Harren 2005; Gershenson et al. 2003) to understanding the role of commonality among components and modules (Corbett and Rosen 2004), to optimizing the definition of modular architectures (Gao et al. 2009; Yu et al. 2007; Fujita 2006). Combined, the focus of these efforts is to understand where modularity and commonality may be achieved, leading to the definition of a generalized architecture.

3.4.2 Material selection

A related aspect of the *Physical Architecture* stage is *Material Selection*. Here, designers must build upon the established architecture and define the range and combination of materials that support the possible customization opportunities.

From the literature review, the material selection phase of embodiment and detailed design can be classified into three categories: module identification, problem formulation and configuration strategies. Module identification research directly picks up from the decisions made when defining the physical architecture and works toward identifying a customer-oriented product concept (Chen et al. 2005). The goal of this work is to define elements that are common or similar enough to turn into modules when system requirements are known and the architecture has been determined, but no parts or components have been defined (Hölttä-Otto et al. 2008). Module identification is a significant challenge, however, and multiple metrics and measures have been defined to accommodate this step. For example, it has been proposed that module similarity can be compared using input/output functional relationships and physical properties (Hölttä-Otto et al. 2008). Other works explore modular identification using cluster analysis (Dai and Scott 2004) and graph grammars (Du et al. 2002a, b, 2003). Graph grammars have an advantage of providing a visual representation of configuration possibilities and are a first step at developing a set of production rules. They can be used to define aspects of the product that should be attached, removed, swapped, or scaled (Du et al. 2003). However, they do not replace decision-making tools, they simply are an effective means of conveying information once decisions have been made about what to offer.

While research in module identification dictates how the product might change, it does not describe why it should change. Research in this step addressed this aspect of design by stating that while a product family targets a specific market segment, it is the variants that need the specific need sets within that segment (Du et al. 2001). Here, product variants are derived from common bases and design parameters; components and assembly structures are embodied in response to the set of functional features desired by the consumers. The challenge is defining the metrics and measures used to assess an effective product family design. One approach toward problem formulation, for example, uses a combination of conjoint analysis and Kohonen association techniques (Chen et al. 2005). In this work, conjoint analysis is used to obtain customer preferences for different design alternatives, and Kohonen association is used to solicit customer desirability between design specifications and design alternatives. Performance of the product family to some designer-defined objective and product commonality is a common problem formulation approach used to arrive at final variant designs (Fellini et al. 2005, 2006; Jiao and Tseng 2000). While the commonality indices are straightforward—looking at a combination of components and processes—the definition of performance loss constraints is more nuanced. A fundamental assumption of this approach is that the customer cares, or identifies with, a performance loss measure as defined by the designer. A different approach is to minimize cost while ensuring that desired modules are present and that there are no compatibility problems (Yeh and Wu 2005). However, desirability of modules is not well defined in this work and must be further explored by linking information from the marketing domain. Finally, Williams et al. (2007) integrates aspects of customer demand, range of variety to be offered and analysis and modeling of demand into a single problem formulation. Designer preferences are mathematically modeled using a utility-based comprise decision-support scheme, yielding a utility function for each objective in the multiobjective problem formulation. However, the paper does not address how to model the inner workings of each objective in any specific manner. The integrated nature of the different domains is highlighted in this paper, and modeling these interactions is left as a source of future work.

Once a problem formulation has been defined, the next step is to design the process of product configuration. An important challenge associated with this step is that the variability left open to the consumer must be done in a way that avoids "mass confusion" (Chen and Wang 2010). That is, since a customer will be involved in the decision-making process of product configuration, the knowledge gap between customers and salesman and designers must be understood (Chen and Wang 2010; Siddique and Ninan 2007). A proposed solution is the development of product configuration rules (Chen and Wang 2010) and product configuration models (Yang et al. 2009) to facilitate the product configuration process. Huang et al. (2008) explore a constraint-based product configuration approach where configurations are classified as being rule-based, model-based or case-based. These constraints allow information to flow from product model to analysis to final configuration to ensure design feasibility. Finally, this notion of capturing and using knowledge of the configuration process also extend to part configuration. Myung and Han (2001), for example, store knowledge to speed the process of part modeling and assembly creation. This allows the dimensions of components to be modified as the design is changed.

3.4.3 *Final validation*

A second stage of the *Embodiment and Detailed Design* is that of *Final Validation*. The *Manufacturability* phase is focused on the assessment of the feasibility and cost effectiveness of manufacturing the range of customization with respect to detailed design requirements, given the architecture. This is common in any product development process.

However, this validation stage differs from mass-produced products because of the perceived sensitivity of product success to customization capability. As such, a critical phase is that of *Market Interest*, in which potential consumers are allowed to customize hypothetical offerings. The goal is to validate that the product is working in the ranges that expected for customizable aspects of the product. This also provides a controlled setting in which to see whether individuals are attaining higher perceived utility when compared to static offerings. It would also be important to validate the interaction approach, as it has the potential to reduce the utility of the customized good, as previously discussed.

3.5 Manufacturing, sales and distribution design

This phase of design occurs after the engineering domain has finalized the detailed design decisions associated with the product. As construction of the product is often delayed until the point of order, the previous phases have primarily focused on constraining the design space to a set of viable consumer-enabled customization decisions. Focus now shifts from establishing the parameters of the product—what it might do, how it might look—to establishing how the product will be made and then distributed to the consumer. The design of the manufacturing, sales, and distribution process for a mass-customized product often has higher or additional requirements than a mass-produced product. This is because of the increased variety offered and the act of integrating the customer into the process of defining the final design configuration. The challenge begins with determining how to manufacture the product in a way that supports the customization opportunities identified in the previous phases.

3.5.1 *Develop approach for manufacturing*

The act of developing a manufacturing approach for mass customization encompasses two distinct steps: technology and process identification. From a technology perspective, research looks to develop the needed technologies that enable production consistent with mass production rather than craft production. Notably, leveraging intelligent and agile manufacturing approaches is critical to delivering truly custom goods. The system for customized clothing from Lu et al. (2010) can generate clothing patterns using CAD techniques based on the collected dimensions, use CNC laser cutting to cut fabric into pattern pieces automatically and integrate the processes of garment sewing.

A representative list of efforts include selective laser melting (Vandenbroucke and Kruth 2007), combining reconfigurable molds and CNC machining (Kelkar and Koc 2008), reconfigurable robotic systems (Bi et al. 2004; Zangiacomi et al. 2004) and rapid prototyping systems (Bateman and Cheng 2002). Limitations of these technologies are also highlighted in the literature (Tuck et al. 2008), such as the single material at-a-time constraint associated with rapid prototyping machines (Bateman and Cheng 2002).

While the technology used to produce mass-customized products is important, the larger challenges come from designing the manufacturing process. Here, research has focused on specific areas—controlling inventory and product construction—while some have focused on the more general manufacturing process. Research focusing on product inventory can be linked to the development of product complexity measures (Zhang and Efsthathiou 2006), where it was found that the number of stock locations may actually play a more significant role than variety (number of variant designs). Additional efforts in the area of inventory also focus on bill-of-material (BOM) generation to unify BOMs and routing information to make production more efficient (Zhang and Efsthathiou 2006; Du and Jiao 2005; Jianxin et al. 2000; Tseng et al. 2005), the use of RFID to track components and subsystems (Chen and Tu 2009) and generalized master models and electron catalogs to serve as reference build structures (Yang et al. 2007; Ma et al. 2008). The motivation behind these works is to facilitate actual product construction. This is needed because actual product construction is made more difficult from the delay in order penetration point and the fact that construction is postponed until the point of sale (Partanen and Haapasalo 2004; Brun and Zorzini 2009). To combat these challenges, modularity is often championed as the most effective means of achieving the necessary postponement, highlighting the ramifications of design decisions made in the conceptual and embodiment phases of design.

Efforts focusing on the entire manufacturing approach highlight the challenges associated with resource management in a mass customization paradigm. A common theme is that a successful manufacturing approach is capable of integrating the manufacturing process, information technology for both product and customer data management, and the management structure (Zhao and Fan 2007; Waller 2004; Fan and Huang 2007; Wang 2009). However, while these works comment on the challenges of the problem, no overarching framework or process is presented to solve this problem. QFD is proposed as one approach to link business process to business function, but this is done at a very high level (Zhao and Fan 2007). Other work has linked information management to build-to-order systems through five basic requirements: speed, simplicity, certainty, visibility and clarity. However, no metrics are provided to quantify these terms.

3.5.2 *Design supplier network*

In much of the MC work, an underlying assumption is that the manufacturer who interacts with the consumer builds the final version of the product after the point of sale. The material for product construction, however, comes from a supplier network capable of supplying the necessary raw materials. In a mass customization environment, the foundation of this supplier network is challenged by the need for increase part variety and increased inventory necessary to support product customization. Research in this area has explored the use of data-mining techniques and QFD in supplier selection (Ni et al. 2007) and data management using XML between the manufacturer and the supply chain (Turowski 2002).

3.5.3 *Develop approach for distribution*

Design of the manufacturing approach and supplier network allows for the product to be built once an order is placed. However, in a mass customization paradigm, an order is not placed until the point of sale. This phase involves the actual interaction with the customer where their integrated design decisions finish the design such that it can be built. Gathering this order information requires managing the flow of information between the customer, the sales office and the technical offices in ways that minimize the need for repetitive activities and minimize configuration errors in production (Salvador and Forza 2004). Controlling this flow of information can be handled by manipulating choices available to consumer by defining one of three MC models (Alford et al. 2000). These MC models will have been defined earlier in the *Concept Generation* phase of the process. By allowing customers to change either the product's core (fundamental architecture changes), options (selecting from a list), or service components (warranty, sales price, etc.), the flow of information can vary from great to relatively small.

The logistics associated with global product launch is explored by Bruce et al. (2007) by drawing on the experience of two firms. In this work, it is found that while some aspects of the launch process may be standardized to maintain efficiencies, some aspects (especially at the regional level) may benefit from customization. Categories of country mores, language and colloquialisms, and technology infrastructure are identified as key areas of customization to increase local market acceptability and social/regulatory expectations. Effectively managing the flow of information during this phase can also facilitate after-market customization opportunities (Graessler 2003).

The arrival of an order allows for the construction of a product to commence. The challenge at this phase mainly addressed in the research is the scheduling of individual orders. Publications in this area tend to focus on the development of computer software or web-based tools that can be used to handle the complexity associated with small batch orders (Zangiacomi et al. 2004; Yao and Carlson 2003; Barnett et al. 2004; Forza and Salvador 2002). This requires real-time status updates and the ability to track to the product through the various phases of construction. There is little validation or theory presented in many of these papers, though some do attempt to introduce a multiobjective problem formulation that can be weighted in various manners to manipulate the supply chain schedule (Yao and Liu 2009).

3.5.4 Develop distribution network

Finally, developing a distribution network focuses on granting the ability to control manufacturing facilities from geographically distant locations while minimizing the distance to the customer. By postponing construction to the point of sale, mass customization provides opportunities to remove the need for massive distribution systems by focusing on getting products to individuals (Bateman and Cheng 2002). The presence of satellite manufacturing facilities can provide opportunities to reduce shipping and wait times while maintaining a network capable of maintain certain economies of scale.

This section highlights the importance of design decisions made with respect to how the product is made in a mass customization paradigm. While the previous sections addressed the challenges and advances in consumer integration, architecture identification and customization frameworks, those outcomes are only made possible by having the flexibility and technology needed to manage information flow and control inventory.

3.6 Proposed individual consumer design process

Paralleling the design process under control of the design firm, there is a consumer-side design process that will be traversed as part of the distribution phase of the design process in Fig. 1. Zhang and Chen (2008) looked at key co-creation activities (KCA) with consumers important to satisfying "personalized demands," and customerization capability (CC) in a study of multiple Chinese firms. They find that involving consumers in the design process prior to final production may be critical to success. In light of these findings, it is desirable to consider the consumer as a designer (Risdiyono and Koomsap 2013), though working in a reduced design space that has been bounded by the firm. Specifically, the consumer-side design process begins as manufacture of a specific custom good is requested. That consumer-side process is shown in Fig. 2 and is explained briefly here.

3.6.1 Product planning

3.6.1.1 Identify individual consumer's needs The consumer identifies their individual subset of user needs, likely from a set of needs developed by the design firm.

3.6.1.2 Identify individual characteristics Specific user characteristics (e.g., anthropometric measurements) that inform and constrain the design solution are submitted. While there are many web-based tools for this type of information submission, it is important to consider more sophisticated approaches to improve resolution of idiosyncratic data. For example, Lu et al. (2010) present an intelligent system for customized clothing making. Body dimensions can be generated from 3D scans or 2D photographs.

3.6.2 Requirement specification

3.6.2.1 Identify individual consumer's needs The individual needs and characteristics of a consumer are mapped by the design firm to system requirements. These system requirements then drive the latter stages of the design process.

3.6.3 Conceptual design

3.6.3.1 Concept generation The design firm generates potential solution concepts from the technically feasible and economically attractive regions of the design space that has been developed through the process of Fig. 1. The consumer is not involved with this stage because it is assumed the solution space is set; instead, potential concepts are offered.

3.6.3.2 Concept selection The consumer, often with some form of help from the design firm, will select the concept that they prefer. As an example, Lee and Kwon (2008) provide a web-based recommendation mechanism that considers causal relationships among quantitative and qualitative factors. In comparing their approach to traditional recommendation tools, they find that integration of causal mechanisms between quantitative and qualitative factors improves consumer decision satisfaction. Kelkar and Koc (2008) use information from customers gathered through e-commerce, leveraging knowledge discovery and data mining to filter consumer information—specifically, semantic data—and offer appropriate products to fit their needs, an approach that could be adopted here.

3.6.3.3 Concept validation The individual consumer approves the overall concept.

3.6.4 Embodiment and detailed design

3.6.4.1 Physical architecture The consumer, often with some form of help from the design firm, will identify the layout, connections of subsystems and material choices. A specific case study that provides for consumers participating in the physical architecture layout is provided by Juan (2009). This work presents a system to support decision making in housing customization using a combination of case-based reasoning (CBR) and a genetic algorithm (GA). A customer is able to participate in the design process by customizing the house according to one's preferred layout, finishing and budget, without time-consuming communication with professional designers. Ninan and Siddique (2006) provide a configurator approach that converts user requirements into hypothetical designs through optimization. However, if the product does not yield a feasible design, the user is asked to select dimensions that can be altered to move toward a feasible solution. Siddique and Boddu (2004) present a graph grammar-based approach that presents the customized product to the user while concurrently creating product construction and assembly steps. Tseng and Chen (2006) provide a product configuration tool that leverages constraints based on customer needs, essential and optional parts, and dependence and mutually exclusive relationships among parts. The literature review of Fogliatto et al. (2012) highlights a number of other "real-world" configurator examples.

3.6.4.2 Final validation In this stage, the consumer approves the design for look, function and performance. The design firm must ensure they can produce the product to specification.

3.6.5 Manufacturing, sales and distribution

In this stage, the company must accept payment, manufacture (fabricate, assemble, configure, etc.) and distribute the mass-customized product. While this stage is essentially execution, it contains a number of non-trivial problems as discussed in the previous section.

This objective of this section was to provide an overview of mass customization literature specifically contextualized in the design process of the firm and the consumer. Based on this review, several conclusions and opportunities for investigation are discussed in the next section.

4 Conclusions and opportunities for advancing the mass customization paradigm in practice

As design researchers and practitioners interested in the potential of MC, the review of literature presented in this paper represents the output of a curiosity regarding the state of practice and how it maps to a process that might be carried out by firms. Though the literature review is not exhaustive, it is representative of the state-of-the-art in MC over the last 12 years.

By mapping the reviewed literature to an envisioned design process, it allows one to assess the "density" of effort in MC with respect to the process focus. From this review, it is evident that there is significant effort in the engineering and distribution-domain-related stages of *Embodiment and Detailed Design*, and *Manufacturing, Sales and Distribution* in Fig. 1. Primarily, these works take form in modularity, product families, agile manufacturing and production automation research. There is also significant effort in the area of product configurators for purposes of integrating the customer as part of the design process, reflected as part of the *Embodiment and Detailed Design* phase of Fig. 2. This existing literature represents an excellent resource from which to draw and develop best practices for firms interested in MC for these specific phases of MC product development and delivery.

With respect to other aspects of the MC design process of Figs. 1 and 2, there are a number of opportunities for future investigation and development. These investigations might be informed by existing literature that parallels MC development factors while not being focused specifically on MC. The remainder of the paper describes these opportunities.

4.1 Customer needs and preference assessment tools

The limited volume of research in the area of preference assessment for MC demonstrates that there is opportunity for more approach development focused on assessing needs and preferences in the context of MC. Need and preference assessment is important when developing the *Coarse Market Assessment* (Fig. 1) that leads to creation of customizable products. Specifically, adapting current approaches based in discrete choice theory to establish the appropriate preference resolution may be required. Examples of such approaches are highlighted in Sect. 3.1. The application of discrete choice models is attractive because of its ability to represent heterogeneity in consumer preferences (Olewnik and Hariharan 2010; Donndelinger et al. 2008; Kumar et al. 2009; Shiau et al. 2007; Turner et al. 2011; Porterfield and Ferguson 2012). However, the capabilities of discrete choice models are limited and may not be robust enough for MC applications. For example, the attributes considered in a discrete choice survey may primarily be useful for only functional aspects, model form is often compensatory, and the cognitive burden placed upon the survey respondent can quickly become prohibitive. In recent work, we attempt to raise this issue specifically (Ferguson et al. 2011).

Tailoring these emerging methods to MC may be a viable approach that could have immediate impact on the paradigm. However, even tailored approaches may not be capable of capturing preference information for aspects like esthetics. Some approaches to incorporate preferences that deviate from discrete choice methods are also reviewed in Sect. 3.1. More importantly, it may be that need elicitation and preference assessment techniques must be pulled from work outside the specific applications of MC and/or engineering design research (Zhou et al. 2012; Fuentes-Fernandez et al. 2009, 2010; Jiao et al. 2007; Durugbo and Riedel 2013; Wang and Tseng 2011; Luh et al. 2012a; Arora et al. 2011; Li et al. 2013). We see opportunity to bring these theoretical bases together to assist in building complete customer preference profiles that support MC.

4.2 Handling requirement specification and conceptual design

The literature focused on developing requirement specifications for the MC design process (Sect. 3.2) appears quite limited based upon our search. The specific opportunity here is to develop methodologies that assist designers in converting coarse market assessment (customer requirements) into appropriate technical requirements and customization ranges. Research is needed to explore if existing requirement management approaches (Simpson et al. 2012; Liu et al. 2010; Bernard 2012; Baxter et al. 2008; Morkos et al. 2012) can be used in, or extended for, MC. Developing technical specification from customer needs, even with available tools, represents a difficult step in a standard product development process. It is envisioned that doing this for MC will be even more difficult given the need the manage customization ranges and finer customer heterogeneity.

Similarly, methodologies for concept generation and selection that are focused on customizable product development are not well represented in the literature. Again, it may be that adapting existing tools is an ideal approach, but studies are necessary to quantify the outcomes for MC applications in comparison with standard product development. Such approaches might include standard practices like the gallery method and morphological matrix (Ulrich and Eppinger 2000) or advanced techniques like “subjective objective system” (Ziv-Av and Reich 2005) and others (Helms and Shea 2012; Liu et al. 2011; Yilmaz et al. 2010; Augustine et al. 2010). Adapting these conceptual design methods to address aspects of system architecture, customization mechanisms and customer interaction is a particular approach suggested in our process of Fig. 1. Yet, this is not to imply that it is *the only* approach.

4.3 Application in the development of durable goods

A significant shortcoming of the methods reviewed lies in the application of the methods for the design of mechanical systems and manufactured products (i.e., durable goods like vehicles and consumer appliances) The MVP method from Liechty et al. (2001) is applied to the customization of web services. Similarly, the work from Fogliatto and da Silveira (2008) is applied to a service problem (natural gas). Applying these methods to manufactured products would add a significant challenge since information regarding pricing and constraints is often dictated by the technical domains of engineering and distribution; information more challenging to represent early in the design process. There are real-world examples (e.g., Dell and Trek Project One), however, the “algorithms” that guide development of these custom goods are proprietary and therefore provide limited insight for others interested in MC.

The devolved manufacturing approach by Bateman and Cheng (2002) will add another layer of complexity, that of “design for customization.” Much consideration will need to be given to define exactly how a product can be customized, with most customization taking place at the “interface” with the user. Analysis to determine the commercial viability of an individualized product and the financially optimum level of customization will be necessary, as will appropriate market research to identify potential markets/products where customization is at a premium (Liu et al. 2012). This is representative of an overall lack of metrics specific to MC that may be important to “go, no-go” decision making during the development process.

These challenges in manufacturing and delivery have created an environment in which the distribution domain, like the marketing domain, pushes additional constraints on the engineering domain in developing architectures capable of MC. These additional constraints reinforce the use of modularity and product platforms as the primary approach for MC in many firms (Sered and Reich 2006; Dobrescu and Reich 2003; Tsai et al. 2013). Further, the need to deliver products as quickly as possible limits fabrication options. An important question resulting from this conclusion is: "How should the product development process be evolved to reflect the challenges of information flow toward the engineering domain to facilitate the increased concurrency in the development of mass-customized goods?" Fig. 1 demonstrates that such considerations raise the level of multi-domain activity and information requirements within the *Conceptual Design* phase.

4.4 Internal and external information mapping and information technology

The linking of information between engineering and product activities is always critical in the design of complex systems. Mass customization, by nature, will make even simple design problem more complex. This is highlighted by the concurrent nature of MC product development, as illustrated by Fig. 1, and underscores the critical nature of information handling between disciplines, design teams, employees and customers.

As a matter of practice, the methodologies aimed at consumer preference assessment and consumer-as-designer integration represent barriers in their application due to their complex nature (Bardakci and Whitelock 2003; Fogliatto and da Silveira 2008; Fung et al. 2004; Liechty et al. 2001). These methods stand out due to their basis in decision and behavioral theory, which is still immature and yet unsubstantiated with regard to validity in product development research and practice. Further, these methodologies would require integrated design teams that include marketing experts and engineers in execution, a practice that has certainly grown over the last two decades but is far from ideal for many product development firms. The development of software applications that automate these methodologies would help in easing the complexity of application, but the issues of validation and effective design teams must be resolved.

Technology can also be used to facilitate needs identification and preference assessment through the use of virtual prototypes and augmented realities (Carulli et al. 2012; Luh et al. 2012b). These environments allow customers to gain experience with a product without the expense and tooling associated with building a physical prototype. However, such systems are expensive to build and can lead to increased time in the design process. These environments may be best suited for customized products in high-cost environments where the market for customization is small. Pursuing a proper balance of fidelity in the virtual systems may be the most effective design strategy. For example, if general architecture decisions are still being made about the product, the level of detail necessary in the virtual prototype should only be as extensive as necessary to guide that decision. As more detailed design work is pursued, the prototype models should be updated to reflect a finer level of granularity.

This reliance on information technology is likely needed if customers are to finish a design and create products with a higher value (Risdiyono and Koomsap 2013). However, this benefit can be tempered by the challenges associated with product configuration. In addition to the design considerations and testing that must go into the product configurator (Haug et al. 2012), putting the human-in-the-loop may require the generation of initial starting points (Mavridou et al. 2013) and the ability to ensure that the desired product configuration is complete and feasible (Yang and Dong 2013). The challenge here is that when the customer acts as designer, the configurator tools must be capable of addressing the knowledge/expertise gap that is likely to be present.

Perhaps the largest amount of research on information flow in MC occurs in the distribution domain, where much of the literature focuses on the fabrication and assembly activities. Remaining challenges that must be addressed can be categorized as issues of approach complexity or of organizational culture. For example, the algorithm from Yao and Liu (2009) gives appropriate consideration to information needs and critical aspects of production decisions for MC. However, the approach is daunting in its complexity and unlikely to be implemented by firms unless significant effort is put into automating the method through software.

Looking at organizational culture, Waller (2004) highlights the five most critical factors—speed, simplicity, certainty, visibility and clarity (all of which could potentially be MC specific metrics). However, the organization of lead firms and suppliers would likely require a firm to establish a subsidiary focused on MC rather than integration of the approach with current practice. Similarly, a key takeaway from Barnett et al. (2004) is that typical CIM infrastructures may be too rigid to meet the constantly changing need of mass-customized manufacturing. This demonstrates that information technology itself can be a barrier to MC if it is not structured with appropriate flexibility and autonomy. In general, the design of mass-customized goods requires effective and agile IT infrastructures capable of supporting information sharing within and between domains and the development of custom applications that operationalize best practice in MC product development.

Finally, Pitta et al. (2004) recognize that information must be shared across the spectrum of the organization, especially if a firm is to maximize "lifetime customer value" (i.e., the financial return that can be generated through maintaining a relationship). General processing of the information throughout the design process is not discussed, though recognized as a key issue which begins in the earliest phases of development.

5 Final remarks

The goal of this paper is to provide a representative overview of the state of the MC paradigm as it pertains to engineering design. By exploring the current state of the MC literature, areas of strength and weakness in an MC design process have been identified. This allowed for the identification of critical areas for design research to explore and develop in the previous section.

While Zipkin raises important concerns that the MC paradigm must be used judiciously, it is apparent from the review of the literature that there is much opportunity for moving the paradigm forward to make it a successful product development approach for more firms. To do so, an overarching framework that represents the highly concurrent nature of mass customization is offered as a foundation for mapping information flows, developing metrics that aid decision making and providing context for research and development of methodologies that aid the paradigm. In addition, the process framework should make apparent that pursuing mass customization is a highly strategic consideration that in many cases requires consideration at the highest levels of management. It is hoped that this work provides a useful, current perspective on MC and serves to highlight areas for new and continued progress in the paradigm.

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References

Alford D, Sackett P, Nelder G (2000) Mass customization—An automotive perspective. Int J Prod Econ 65(1):99–110

Arnheiter ED, Harren H (2005) A typology to unleash the potential of modularity. J Manuf Technol Manage 16(7):699–711. doi:10.1108/17410380510619923

Arora N, Henderson T, Liu Q (2011) Noncompensatory dyadic choices. Mark Sci 30(6):1028–1047

Augustine M, Yadav OP, Jain R, Rathore APS (2010) Concept convergence process: a framework for improving product concepts. Comput Ind Eng 59(3):367–377

Bardakci A, Whitelock J (2003) Mass-customisation in marketing: the consumer perspective. J Consum Mark 20(5):463–479. doi:10.1108/07363760310489689

Barnett L, Rahimifard S, Newman S (2004) Distributed scheduling to support mass customization in the shoe industry. Int J Comput Integr Manuf 17(7):623–632

Bateman R, Cheng K (2002) Devolved manufacturing. Concurr Eng 10(4):291–298

Baxter D, Gao J, Case K, Harding J, Young B, Cochrane S, Dani S (2008) A framework to integrate design knowledge reuse and requirements management in engineering design. Robot Comput Integr Manuf 24(4):585–593

Bernard Y (2012) Requirements management within a full model-based engineering approach. Syst Eng 15(2):119–139

Bi ZM, Gruver WA, Lang SYT (2004) Analysis and synthesis of reconfigurable robotic systems. Concurr Eng 112(2):145–154

Bruce M, Lucy D, Kenneth B (2007) Delineating design factors that influence the global product launch process. J Prod Innov Manage 24(5):456–470

Brun A, Zorzini M (2009) Evaluation of product customization strategies through modularization and postponement. Int J Prod Econ 120(1):205–220

Carulli M, Bordegoni M, Cugini U (2012) An approach for capturing the voice of the customer based on virtual prototyping. J Intell Manuf. doi:10.1007/s10845-012-0662-5

Chen R, Tu M (2009) Development of an agent-based system for manufacturing control and coordination with ontology and RFID technology. Expert Syst Appl 35(4):7581–7593

Chen Z, Wang L (2010) Personalized product configuration rules with dual formulations: a method to proactively leverage mass confusion. Expert Syst Appl 37(1):383–392. doi:10.1016/j.eswa.2009.05.050

Chen C-H, Khoo L, Yan W (2003) Evaluation of multicultural factors from elicited customer requirements for new product development. Res Eng Design 14(3):119–130

Chen C-H, Khoo LP, Yan W (2005) PDCS—a product definition and customisation system for product concept development. Expert Syst Appl 28(3):591–602. doi:10.1016/j.eswa.2004.12.040

Corbett B, Rosen DW (2004) A configuration design based method for platform commonization for product families. AI EDAM 18(01):21–39. doi:10.1017/s089006040404003x

Dai Z, Scott M (2004) Product platform design through sensitivity analysis and cluster analysis. J Intell Manuf 18(1):97–113

Davis SM (1987) Future perfect. Addison-Wesley Publishing, Reading, MA

Dellaert BGC, Stremersch S (2005) Marketing mass-customized products: striking a balance between utility and complexity. J Mark Res 42(2):219–227. doi:10.2307/30164019

Dobrescu G, Reich Y (2003) Progressive sharing of modules among product variants. Comput Aided Des 35(9):791–806

Donndelinger JA, Robinson JA, Wissman LA (2008) Choice model specification in market-based engineering design. Paper presented at the ASME international design engineering technical conferences and computers and information in engineering conference, Brooklyn, NY

Du J, Jiao Y-Y (2005) Integrated BOM and routing generator for variety synchronization in assembly-to-order production. J Manuf Technol Manage 16(2):233–243

Du X, Jiao J, Tseng MM (2001) Architecture of product family: fundamentals and methodology. Concurr Eng Res Appl 9(4):309–325

Du X, Jiao J, Tseng M (2002a) Product family modeling and design support: an approach based on graph rewriting systems. AI EDAM 16(2):103–120

Du X, Jiao J, Tseng MM (2002b) Graph grammar based product family modeling. Concurr Eng 10(2):113–128. doi:10.1177/1063293x02010002635

Du X, Jiao J, Tseng M (2003) Modelling platform-based product configuration using programmed attributed graph grammars. J Eng Des 14(2):145–167. doi:10.1080/0954482031000091482

Durugbo C, Riedel J (2013) Viewpoint-participation-technique: a model of participative requirements elicitation. Concurr Eng Res Appl 21(1):3–12

Eckert C, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Res Eng Design 15(1):1–21. doi:10.1007/s00163-003-0031-7

Fan YS, Huang GQ (2007) Networked manufacturing and mass customization in the ECommerce era: the Chinese perspective. Int J Comput Integr Manuf 20(2):107–114

Fellini R, Kokkolaras M, Papalambros P, Perez-Duarte A (2005) Platform selection under performance loss constraints in optimal design of product families. J Mech Des 127(4):524–536

Fellini R, Kokkolaras M, Papalambros P, Perez-Duarte A (2006) Commonality decisions in product family design. In: Simpson TW, Siddique Z, Jiao J (eds) Product platform and product family design: methods and applications. Springer Science + Business Media, New York, pp 157–185

Ferguson S, Olewnik A, Cormier P (2011) Exploring marketing to engineering information mapping in mass customization: a presentation of ideas, challenges and resulting questions. Paper presented at the ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Washington, DC, August 28–31

Fogliatto FS, da Silveira GJC (2008) Mass customization: a method for market segmentation and choice menu design. Int J Prod Econ 111(2):606–622. doi:10.1016/j.ijpe.2007.02.034

Fogliatto FS, da Silveira GJC, Borenstein D (2012) The mass customization decade: an updated review of the literature. Int J Prod Econ 138(1):14–25. doi:10.1016/j.ijpe.2012.03.002

Forza C, Salvador F (2002) Managing variety in the order acquisition and fulfilment process: the contribution of product configuration systems. Int J Prod Econ 76(1):87–98

Frutos JD, Santos ER, Borenstein D (2004) Decision support system for product configuration in mass customization environments. Concurr Eng 12(2):131–144

Fuentes-Fernandez R, Gomez-Sanz J, Pavon J (2009) Requirements elicitation and analysis of multiagent systems using activity theory. IEEE Trans Syst Man Cybern Part A Syst Hum 39(2):282–298

Fuentes-Fernandez R, Gomez-Sanz J, Pavon J (2010) Understanding the human context in requirements elicitation. Requirements Eng 15(3):267–283

Fujita K (2006) Simultaneous optimization of module combination and module attributes. In: Simpson TW, Siddique Z, Jiao J (eds) Product platform and product family design: methods and applications. Springer Science + Business, New York, pp 186–223

Fung RYK, Chong SPY, Wang Y (2004) A framework of product styling platform approach: styling as intangible modules. Concurr Eng 12(2):89–103. doi:10.1177/1063293x04044381

Gao F, Xiao G, Simpson TW (2009) Module-scale-based product platform planning. Res Eng Design 20(2):129–141. doi:10.1007/s00163-008-0061-2

Gershenson J, Prasad G, Zhang Y (2003) Product modularity: definitions and benefits. J Eng Des 14(3):295–313

Gilmore JH, Pine BJ (eds) (2000) Markets of one: creating customer-unique value through mass customization. Harvard Business School Press, Boston, MA

Gonzalez-Zugasti JP, Otto KN, Baker JD (2000) A method for architecting product platforms. Res Eng Design 12(2):61–72. doi:10.1007/s001630050024

Gonzalez-Zugasti JP, Otto KN, Baker JD (2001) Assessing value in platformed product family design. Res Eng Design 13(1):30–41. doi:10.1007/s001630100001

Graessler I (2003) Impacts of information management on customized vehicles and after-sales services. Int J Comput Integr Manuf 16(7):566–570

Guilabert MB, Donthu N (2006) Mass customisation and consumer behaviour: the development of a scale to measure customer customisation sensitivity. Int J Mass Cust 1(2–3):166–175. doi:10.1504/ijmassc.2006.008620

Haug A, Hvam L, Mortensen N (2012) Definition and evaluation of product configurator development strategies. Comput Ind 63(5):471–481

Helms B, Shea K (2012) Computational synthesis of product architectures based on object-oriented graph grammars. J Mech Des 134(2). doi:10.1115/1.4005592

Hofer AP, Halman JIM (2004) Complex products and systems: potential from using layout platforms. AI EDAM 18(1):55–69. doi:10.1017/s0890060404040053

Hölttä-Otto K, Tang V, Otto K (2008) Analyzing module commonality for platform design using dendrograms. Res Eng Design 19(2–3):127–141. doi:10.1007/s00163-008-0044-3

Huang GQ, Li L, Lau TL, Chen X (2007) A generic and extensible information infrastructure framework for mass-customizing platform products. Int J Comput Integr Manuf 20(2–3):292–306. doi:10.1080/09511920601150669

Huang Y, Liu H, Ng WK, Lu W, Song B, Li X (2008) Automating knowledge acquisition for constraint-based product configuration. J Manuf Technol Manage 19(6):744–754. doi:10.1108/17410380810888120

Jiang K, Lee H, Seifert R (2006) Satisfying customer preferences via mass customization and mass production. IIE Trans 38(1):25–38. doi:10.1080/07408170500346386

Jianxin J, Tseng M, Qinhai M, Yi Z (2000) Generic bill-of-materials-and-operations for high-variety production management. Concurr Eng 8(4):297–321

Jiao J, Tseng M (2000) Understanding product family for mass customization by developing commonality indices. J Eng Des 11(3):225–243

Jiao J, Zhang Y, Helander M (2006) A Kansei mining system for affective design. Expert Syst Appl 30(4):658–673. doi:10.1016/j.eswa.2005.07.020

Jiao J, Xu Q, Du J, Zhang Y, Helander M, Khalid HM, Helo P, Ni C (2007) Analytical affective design with ambient intelligence for mass customization and personalization. Int J Flex Manuf Syst 19(4):570–595

Juan Y-K (2009) A hybrid approach using data envelopment analysis and case-based reasoning for housing refurbishment contractors selection and performance improvement. Expert Syst Appl 36(3, Part 1):5702–5710. doi:10.1016/j.eswa.2008.06.053

Kaplan AM, Haenlein M (2006) Toward a parsimonious definition of traditional and electronic mass customization. J Prod Innov Manage 23(2):168–182. doi:10.1111/j.1540-5885.2006.00190.x

Kaplan AM, Schoder D, Haenlein M (2007) Factors influencing the adoption of mass customization: the impact of base category consumption frequency and need satisfaction. J Prod Innov Manage 24(2):101–116. doi:10.1111/j.1540-5885.2007.00237.x

Kelkar A, Koc B (2008) Geometric planning and analysis for hybrid reconfigurable modeling and machining process. Rapid Prototyp J 14(1):23–34

Kumar D, Hoyle C, Chen W, Wang N, Gomez-Levi G, Koppelman F (2009) A hierarchical choice modelling approach for incorporating customer preferences in vehicle package design. Int J Prod Dev 8(3):228–251

Kurniawan SH, So RHY, Tseng MM (2006) Consumer decision quality in mass customisation. Int J Mass Cust 1(2):176–194

Lee KC, Kwon S (2008) Online shopping recommendation mechanism and its influence on consumer decisions and behaviors: a causal map approach. Expert Syst Appl 35(4):1567–1574. doi:10.1016/j.eswa.2007.08.109

Li S, Nahar K, Fung BCM (2013) Product customization of tablet computers based on the information of online reviews by customers. J Intell Manuf. doi:10.1007/s10845-013-0765-7

Liao S-H, Chen C-M, Hsieh C-L, Hsiao S-C (2009) Mining information users' knowledge for one-to-one marketing on information appliance. Expert Syst Appl 36(3, Part 1):4967–4979. doi:10.1016/j.eswa.2008.06.020

Liechty J, Ramaswamy V, Cohen SH (2001) Choice menus for mass customization: an experimental approach for analyzing customer demand with an application to a web-based information service. J Mark Res 38(2):183–196. doi:10.1509/jmkr.38.2.183.18849

Liu Z-L, Zhang Z, Yong C (2010) A scenario-based approach for requirements management in engineering design. Concurr Eng Res Appl 20(2):99–109

Liu C, Ramirez-Serrano A, Yin GF (2011) Customer-driven product design and evaluation method for collaborative design environments. J Intell Manuf 22(5):751–764

Liu N, Choi T-M, Tuen C-WM, Ng F (2012) Optimal pricing, modularity, and return policy under mass customization. IEEE Trans Syst Man Cybern Part A Syst Hum 42(3):604–614

Lu J-M, Wang M-JJ, Chen C-W, Wu J-H (2010) The development of an intelligent system for customized clothing making. Expert Syst Appl 37(1):799–803. doi:10.1016/j.eswa.2009.05.089

Luh D-B, Ma C-H, Hsieh M-H, Huang C-Y (2012a) Using the systematic empathic design method for customer-centered products development. J Integr Des Process Sci 16(4):31–54

Luh Y-P, Wang J-B, Chang J-W, Chang S-Y, Chu C-H (2012b) Augmented reality-based design customization of footwear for children. J Intell Manuf. doi:10.1007/s10845-012-0642-9

Ma Y, Jiao J, Deng Y (2008) Web service-oriented electronic catalogs for product customization. Concurr Eng 16(4):263–269

MacCarthy B, Brabazon PG, Bramham J (2003) Fundamental modes of operation for mass customization. Int J Prod Econ 85(3):289–304

Martin M, Ishii K (2002) Design for variety: developing standardized and modularized product platform architectures. Res Eng Design 13(4):213–235. doi:10.1007/s00163-002-0020-2

Mavridou E, Kehagia DD, Tzovaras D, Hassapis G (2013) Mining affective needs of automotive industry customers for building a mass-customization recommender system. J Intell Manuf 24(2):251–265

McIntosh RI, Matthews J, Mullineux G, Medland AJ (2010) Late customisation: issues of mass customisation in the food industry. Int J Prod Res 48(6):1557–1574. doi:10.1080/00207540802577938

Meyer M, Lehnerd A (1997) The power of product platforms: building value and cost leadership. Free Press, New York

Morkos B, Shankar P, Summers JD (2012) Predicting requirement change propagation, using higher order design structure matrices: an industry case study. J Eng Des 23(12):902–923

Myung S, Han S (2001) Knowledge-based parametric design of mechanical products based on configuration design method. Expert Syst Appl 21(2):99–107. doi:10.1016/s0957-4174(01)00030-6

Ni M, Xu X, Deng S (2007) Extended QFD and data-mining-based methods for supplier selection in mass customization. Int J Comput Integr Manuf 20(2–3):280–291

Ninan JA, Siddique Z (2006) Internet-based framework to support integration of customer in the design of customizable products. Concurr Eng 14(3):245–256

Olewnik A, Hariharan VG (2010) Conjoint-HoQ: evolving a methodology to map market needs to product profiles. Int J Prod Dev 10(4):338–368

Partanen J, Haapasalo H (2004) Fast production for order fulfillment: implementing mass customization in electronics industry. Int J Prod Econ 90(2):213–222

Piller FT (2004) Mass customization: reflections on the state of the concept. Int J Flex Manuf Syst 16(4):313–334. doi:10.1007/s10696-005-5170-x

Piller FT, Müller M (2004) A new marketing approach to mass customisation. Int J Comput Integr Manuf 17(7):583

Pitta DA, Franzak F, Laric M (2003) Privacy and one-to-one marketing: resolving the conflict. J Consum Mark 20(7):616–628. doi:10.1108/07363760310506157

Pitta DA, Franzak FJ, Little MW (2004) Maintaining positive returns in the value and supply chain: applying tomorrow's marketing skills. J Consum Mark 21(7):510–519

Porterfield K, Ferguson S (2012) Quantifying customer sacrifice for use in product customization problems. In: Proceedings of the 2012 ASME international design engineering technical conferences and computers and information in engineering conference, Chicago, IL, pp DETC2012-71151

Risdiyono, Koomsap P (2013) Design by customer: concept and applications. J Intell Manuf 24(2):295–311. doi:10.1007/s10845-011-05874

Salvador F, Forza C (2004) Configuring products to address the customization-responsiveness squeeze: a survey of management issues and opportunities. Int J Prod Econ 91(3):273–291

Salvador F, de Holan PM, Piller F (2009) Cracking the code of mass customization. MIT Sloan Manage Rev 50(03):70–78

Sered Y, Reich Y (2006) Standardization and modularization driven by minimizing overall process effort. Comput Aided Des 38(5):405–416

Shiau C-S, Tseng IH, Heutchy AW, Michalek J (2007) Design optimization of a laptop computer using aggregate and mixed logit demand models with consumer survey data. Paper presented at the ASME IDETC & CIE, Las Vegas, NV, September 4–7

Siddique Z, Boddu KR (2004) A mass customization information framework for integration of customer in the configuration/design of a customized product. AI EDAM 18(01):71–85. doi:10.1017/s0890060404040065

Siddique Z, Ninan JA (2007) A grammatical approach for real-time design of engineer-to-order products. J Eng Des 18(2):157–174. doi:10.1080/09544820600733427

Simpson T, Maier J, Mistree F (2001) Product platform design: method and application. Res Eng Design 13(1):2–22. doi:10.1007/s001630100002

Simpson TW, Siddique Z, Jiao J (2006) Product platform and product family design. Springer Science + Business Media, New York

Simpson TW, Bobuk A, Slingerland LA, Brennan S, Logan D, Reichard K (2012) From user requirements to commonality specifications: an integrated approach to product family design. Res Eng Design 23(2):141–153

Suh ES, Weck OLd, Chang D (2007) Flexible product platforms: framework and case study. Res Eng Design 18(2):67–89. doi:10.1007/s00163-007-0032-z

Trek Bicycle Corporation (2013) Project One—Bike models—Trek Bicycle. Trek Bicycle Corporation. http://www.trekbikes.com/us/en/collections/custom_project_one/models/. Accessed 30 April 2013

Tsai C-Y, Chen C-J, Lo Y-T (2013) A cost-based module mining method for the assemble-to-order strategy. J Intell Manuf. doi:10.1007/s10845-013-0736-z

Tseng HE, Chen CC (2006) Coordinating product configuration in the order fulfilment processing: an approach based on the binary tree algorithm. Int J Comput Integr Manuf 19(7):716–726. doi:10.1080/09511920500233616

Tseng H-E, Chang C–C, Chang S-H (2005) Applying case-based reasoning for product configuration in mass customization

environments. Expert Syst Appl 29(4):913–925. doi:10.1016/j.eswa.2005.06.026
Tuck CJ, Hague RJM, Ruffo M, Ransley M, Adams P (2008) Rapid manufacturing facilitated customization. Int J Comput Integr Manuf 21(3):245–258
Turner C, Ferguson S, Donndelinger JA (2011) Exploring heterogeneity of customer preference to balance commonality and market coverage. In: Proceedings of the 2011 ASME international design engineering technical conferences and computers and information in engineering conference, Washington, DC, pp DETC2011-48581
Turowski K (2002) Agent-based E-commerce in case of mass customization. Int J Prod Econ 75(1–2):69–81
Ulrich KT, Eppinger SD (2000) Product design and development, 2nd edn. McGraw-Hill Higher Education, Boston
Vandenbroucke B, Kruth J-P (2007) Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. Rapid Prototyp J 13(4):196–203
Waller B (2004) Market responsive manufacturing for the automotive supply chain. J Manuf Technol Manage 15(1):10–19
Wang W (2009) Toward developing agility evaluation of mass customization systems using 2-tuple linguistic computing. Expert Syst Appl 36(2, Part 2):3439–3447
Wang Y, Tseng MM (2011) Integrating comprehensive customer requirements into product design. CIRP Ann Manuf Technol 60(1):175–178
Williams CB, Allen JK, Rosen DW, Mistree F (2007) Designing platforms for customizable products and processes in markets of non-uniform demand. Concurr Eng 15(2):201–216. doi:10.1177/1063293x07079328
Yang D, Dong M (2013) Applying constraint satisfaction approach to solve product configuration problems with cardinality-based configuration rules. J Intell Manuf 24(1):99–111
Yang QH, Qi GN, Lu YJ, Gu XJ (2007) Applying mass customization to the production of industrial steam turbines. Int J Comput Integr Manuf 20(2–3):178–188. doi:10.1080/09511920601020698
Yang D, Miao R, Wu H, Zhou Y (2009) Product configuration knowledge modeling using ontology web language. Expert Syst Appl 36(3, Part 1):4399–4411. doi:10.1016/j.eswa.2008.05.026
Yao AC, Carlson JGH (2003) Agility and mixed-model furniture production. Int J Prod Econ 81–82:95–102
Yao J, Liu L (2009) Optimization analysis of supply chain scheduling in mass customization. Int J Prod Econ 117(1):197–211
Yeh J-Y, Wu T-H (2005) Solutions for product configuration management: an empirical study. AI EDAM 19(01):39–47. doi:10.1017/s0890060405050043
Yilmaz S, Seifert CM, Gonzalez R (2010) Cognitive heuristics in design: instructional strategies to increase creativity in idea generation. AI EDAM 24(3):335–355
Yu T, Yassine AA, Goldberg DE (2007) An information theoretic method for developing modular architectures using genetic algorithms. Res Eng Design 18:91–109
Zangiacomi A, Zhtjtan L, Sacco M, Boer CR (2004) Process planning and scheduling for mass customized shoe manufacturing. Int J Comput Integr Manuf 17(7):613–621
Zha XF, Sriram RD, Lu WF (2004) Evaluation and selection in product design for mass customization: a knowledge decision support approach. AI EDAM
Zhang X, Chen R (2008) Examining the mechanism of the value co-creation with customers. Int J Prod Econ 116(2):242–250. doi:10.1016/j.ijpe.2008.09.004
Zhang T, Efsthathiou J (2006) The complexity of mass customization systems under different inventory strategies. Int J Comput Integr Manuf 19(5):423–433
Zhao Y, Fan YS (2007) Implementation approach of ERP with MC. Int J Comput Integr Manuf 20(2–3):160–168
Zhou F, Ji Y, Jiao J (2012) Affective and cognitive design for mass personalization: status and prospect. J Intell Manuf. doi:10.1007/s10845-012-0673-2
Zipkin P (1997) The limits of mass customization. MIT Sloan Manage Rev 42(3):81–87
Ziv-Av A, Reich Y (2005) SOS—subjective objective system for generating optimal product concepts. Des Stud 26(5):509–533. doi:10.1016/j.destud.2004.12.001