MASS CUSTOMIZATION: A REVIEW OF THE PARADIGM ACROSS MARKETING, ENGINEERING AND DISTRIBUTION DOMAINS

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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 order to answer the question of “why not?” and to highlight areas for specific research in the MC paradigm. To establish perspective for this work, we consider MC to be a product development approach which allows for the production of goods after a customer places an order which minimize the tradeoff between the ideal product and the available product by fulfilling the needs and preferences of individuals functionally, emotionally and anthropologically. Results of this research were generated by reviewing 88 papers from various journals that span three domains of interest (marketing, engineering, and distribution) and explore proposed methodologies, specific information inputs and outputs, proposed metrics, and barriers toward the implementation of MC. Qualitatively, we show that the lack of MC in application is due to two factors: 1) a lack of marketing tools capable of capturing individual needs that can be mapped to the technical space; and 2) a lack of information relation mechanisms that connect the domains of marketing, engineering, and distribution. In the end it is our belief that MC is realizable and that eventually it will emerge as a dominant paradigm in the design and delivery of products and systems. However, pursuing the opportunities for research presented in this work will hopefully speed this emergence.

1. INTRODUCTION AND MOTIVATION
The concept of mass customization (MC) was put forth by Davis [1] 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. The fundamental question to be explored in this research is – “why not?” 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 [2]. 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. The objective is to highlight areas for specific research in the MC paradigm.

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 MC is a paradigm that would provide consumers “exactly what they want when they want it” [1]. This view of MC sounds like a Star Trek
"replicator" [3] 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 which sets the context and perspective for this research is that MC is a product development approach which allows for the creation of goods which minimize the tradeoff between the ideal product and the available product by fulfilling the needs and preferences of individuals functionally, emotionally and anthropologically. This definition also agrees with that of Piller and Muller [4], who suggest that there are three types of customization: style (emotional), fit and comfort (anthropological), and performance (functional). The critical element to be recognized here is that in the consumer space, tradeoffs must be minimized across three dimensions and achieving MC should be thought of as a multiobjective problem.

Another critical element of discussion, again in agreement with Piller and Muller [4], is that MC is defined by a fixed solution space. This is different than traditional craft customization which has an 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. Taken with the goal of minimizing tradeoffs, this necessary assumption means that identification of the core product architecture is critical and must rely heavily on advancements in market assessment techniques which map to technical aspects of engineered goods.

Finally, the view of MC taken here has one other key parameter: that the final configuration of the product is not produced (i.e. fabricated or assembled) until the customer places an order. Ordering a Dell computer is an example of MC - one which relies on modularity for final assembly. On the other hand, purchasing a car with a manufacturer-defined options 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. An empirical study of approaches to MC which rely on modularity and consumer input at various states of the production process is provided by Duray et al. [5]. Here, the tools and technologies available to mass customizers are classified into four categories based on two dimensions (when the customer becomes involved and modularity type). However, customer involvement is only one aspect of mass customization.

The methodology used in this research is a review of the literature from the last decade to better understand the process of MC from input to output. This can be a daunting task as the term "mass customization" returns plenty of results in most search engines whether they be internet-wide (e.g. Google) or journal database specific. For example, a search for the term "mass customization" in Google returns 605,000 results for the web and 48,000 results for the "scholar" filter that is part of the Google search engine. Similarly, searching databases of archived journals like ScienceDirect returns 3,044 results.

Given the ubiquitous existence of the MC topic, a specific framework to guide the search for literature on MC was devised. That framework is demonstrated in Figure 1, which shows 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). Each MC paper reviewed as part of this research was assigned to one of these classifications. Occasionally, a paper addressed issues across these classifications and is noted as a "total process" paper.

Based on this framework, a literature search that spans 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.

![Figure 1. Categorization of the MC process](image)

This review effort is motivated by a desire to understand the MC process from input to output. General conversations among the authors over time led to a number of questions representing an engineering design perspective. Once reading began, these questions were refined to a pertinent set that could be applied across the categories to all the papers reviewed. These questions are:

1. A) Is the methodology described in the paper intended to support MC directly? B) 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?
Hypothesis 1: The MC paradigm suffers from a lack of marketing tools capable of capturing needs at the level of individual which can be mapped to technical aspects of MC products/systems.

Hypothesis 2: The MC paradigm suffers from a lack of information relation mechanisms to connect the broad categories of marketing, engineering and distribution.

An antagonistic view (or perhaps just a more realistic view) of MC is offered by Zipkin [6]. In his article regarding limitations of MC, he casts the paradigm as 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.

In the end, it is our belief that MC is realizable and that it will eventually emerge as a dominant paradigm in the design and delivery of products and systems. It is the opinion here that understanding the opportunities for research that belie these hypotheses can speed this emergence. However, it is important to point out that the realities highlighted by Zipkin are important ones to work through for any company considering MC. They also provide a nice set of overarching challenges that align with the three domain perspective of MC represented in Figure 1.

This paper is set up in the following way. Sections 2 through 5 breakdown the results of the literature review according to the categories and questions posed here, and discusses these findings in greater detail citing specific references. Section 6 highlights specific research challenges and opportunities for MC.

2. RESULTS OF THE LITERATURE REVIEW
Table 1 presents the results from the literature review as they pertain to the six questions discussed in Section 1. This summary of results is meant to serve the research community by classifying the existent literature by design domain (marketing, engineering or distribution) and focus as correlated by the six questions.

The following sections break down more specific findings for each of the three domains identified in Figure 1. The focus is to highlight specific insights, challenges, information inputs/outputs, and metrics which have been developed and reported in the literature. The papers referenced in detail in the following sections are those that provided some answers to at least three of the questions presented in Section 1. There is no specific information provided regarding research efforts which
answer research question two - readers are encouraged to seek
the references from Table 1.

3. MC AND THE MARKETING DOMAIN

For MC to be a successful paradigm, understanding individual consumers and meeting their needs and preferences is fundamental. As envisioned by Davis each individual customer represents a market [1], leading Gilmore and Pine to advocate that these "markets of one" are no longer a possibility but in fact exist [2]. In suggesting this, Gilmore and Pine are highlighting the fact that increased access to information from consumers, and improved modeling techniques that can distinguish heterogeneous preferences, make it possible for firms to generate profiles of these "markets of one" in a way that still leverage economies of scale in the downstream engineering, manufacturing and distribution tasks.

Furthering this point, Gilmore and Pine highlight the need for individual consumer information achieved through learning relationships and potential metrics introduced by researchers which should/could be the basis for modeling decisions regarding MC as a viable business paradigm. These metrics include variety index, sacrifice gap, customer skew, and sacrifice skew, which are all described and promoted as parameters that could be used to quantify important aspects of MC from the customer perspective [2].

In reviewing literature that fits the marketing domain category two research themes emerged: 1) need and preference assessment for MC; and 2) assessing customer readiness for MC. The subsequent subsections review work that fit these themes in the context of the motivating research questions from Section 1.

3.1 MC METHODS IN THE MARKETING DOMAIN

Exploring methodologies for MC in the context of the marketing domain led to the identification of two distinct themes. In this section, each of these two themes is discussed.

Need and preference assessment
In exploring "methodologies" applicable to the marketing domain, the expectation was to find research focused on the development of methods that would aid firms in assessing the needs and preferences of consumers at an individualized level and map that information to design specifications necessary to meet highly heterogeneous needs and preferences. Along this line, Liechty and Ramaswamy [6] develop a Bayesian based multivariate probit (MVP) approach for menu-based choice. This methodology is intended to support menu-driven choice scenarios where features, constraints and pricing may be a function of previous features selected (e.g. graphics cards choices are limited by overall PC family at Dell). Comparisons to alternative approaches and to conjoint based approaches show that this method can be superior. This work represents an

<table>
<thead>
<tr>
<th>Research Question</th>
<th>Marketing</th>
<th>Engineering</th>
<th>Distribution</th>
<th>Total Process</th>
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<tbody>
<tr>
<td>RQ1-A: The paper describes a methodology intended to support MC development.</td>
<td>[7], [8], [9], [10], [11], [12], [13]</td>
<td>[14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]</td>
<td>[35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47]</td>
<td>[48], [49]</td>
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<td>RQ1-B: The paper describes a design method which is not MC specific but has clear implications for MC.</td>
<td>[50]</td>
<td>[51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]</td>
<td>[67], [68], [69], [70], [71], [72], [73], [74], [75]</td>
<td>[81]</td>
</tr>
<tr>
<td>RQ3: The paper describes specific information inputs and the source of those inputs.</td>
<td>[7], [76], [7], [8], [9], [10], [77], [11], [4], [78]</td>
<td>[35], [38], [14], [41], [42], [16], [18], [19], [43], [44], [46], [21], [22], [23], [24], [25], [26], [28], [79]</td>
<td>[34], [35], [36], [80], [39], [40], [41], [44], [71], [72]</td>
<td>[80]</td>
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<td>RQ4: The paper describes specific information outputs and the use of those outputs.</td>
<td>[7], [8], [9], [11], [16]</td>
<td>[13], [36], [14], [82], [40], [15], [18], [19], [43], [44], [46], [21], [22], [28]</td>
<td>[34], [35], [36], [37], [38], [77], [40], [41], [44], [71]</td>
<td>[80]</td>
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<tr>
<td>RQ6: There are significant barriers to implementation.</td>
<td>[7], [83], [7], [8], [9], [10], [4]</td>
<td>[36], [38], [14], [55], [19], [44], [45], [46], [21], [22], [23], [24], [25], [26], [33]</td>
<td>[35], [36], [65], [77], [39], [40], [84]</td>
<td>[80]</td>
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<td>RQ5-A: There are MC specific metrics described in the paper.</td>
<td>[7], [14], [7], [10], [11]</td>
<td>[13], [15], [21], [24], [54]</td>
<td>[80], [43], [44]</td>
<td>[47]</td>
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<td>RQ5-B: Equations are defined for these metrics.</td>
<td>[7]</td>
<td>[13], [15], [21], [24], [54]</td>
<td></td>
<td>[47]</td>
</tr>
<tr>
<td>RQ2: The paper quantifies effects of using MC.</td>
<td>[85], [86], [87], [4]</td>
<td>[16]</td>
<td>[88], [89], [90]</td>
<td>[91]</td>
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Table 1. Breakdown of references by research question and domain
important combination of traditional market modeling techniques and the IT infrastructure necessary for effective market assessment in the MC paradigm. Similarly, Fogliatto and Silveira [8] focus on developing a method to determine the optimal choice menu design based on consumer segments which leverage traditional market research techniques, cluster analysis and experimental design techniques, use of stated preference models, and logistic regression.

Frutos et al. [9] propose a decision support system for facilitating designer and customer collaboration in the process of selecting production configuration in MC environments. The set of technical, aesthetic and financial constraints are defined interactively by designers and customers and multiattribute decision modeling techniques are used to determine the value of customization. Fung et al. [10] propose a working model of customers' preferences to product styling. In doing so, the work examines the relationships between product style and fashion trends on consumer preferences and the challenge this imposes for MC. The motivation is that by focusing on "pleasure" gained from aesthetic properties in addition to functional properties, the desire for a product can be increased. Furthermore, a particular style can become reusable if it becomes a fashion - which means that it is liked by a critical mass of consumers - permitting greater efficiency by promoting component reuse.

Assessing customer readiness
In addition to methodologies that provide firms a basis for assessing the market - in terms of needs and preferences - with regard to what aspects of a product should be made customizable, a number of researchers have looked at establishing whether or not MC is viable as a product development approach. This second theme can be generalized as "customer readiness" for MC.

Bardacki and Whitelock [7] put forth a decision framework for establishing "customer readiness" which consists of three components: 1) customer willingness to pay a premium for customization, 2) customer willingness to wait to receive their customized product, and 3) customer willingness to spend time to specify preferences when ordering. Similarly, Guilabert and Donthu [11] focus on the development of a scale which measures 1) customer sensitivity toward customization in general and 2) differences in customization sensitivity across product/service categories. The motivation lies in overcoming the general lack of knowledge of how MC strategies and market theory (particularly consumer behavior) must be integrated to make MC a successful paradigm. In developing this scale, two dimensions represented by the CCS (Customer Customization Sensitivity) metric are used as a basis: 1) consumers having an inherent preference toward or against customized offerings and 2) consumers preferring more or less customization dependent on product/service under consideration. The authors point out that their scale can be used to examine how consumers feel about customization and assess if potential consumers will be pleased. In addition, firms could easily modify the scale to assess customization sensitivity for specific products/services. Kaplan et al. [12] use base category information (frequency of use and need satisfaction) to identify users most likely to adopt a mass customized product. Surveying allows for perceived usefulness, ease of use, and behavioral intent to be captured.

These two "themes" - understanding consumer preferences in advance of designing the product and determining consumer "readiness" for customization - that dominated the literature in the marketing domain suggest that development of MC products requires a formal commitment to the paradigm on the part of firms. That is, simply adapting existing market assessment tools rooted in discrete choice theory to the customization problem will not suffice. Despite this suggestion, the number of market assessment based methods existent in the literature is far less than one would expect considering the age of the paradigm.

3.2 MC INFO I/O IN THE MARKETING DOMAIN
Based on the "themes" uncovered in Section 3.1 there are two types of information to be expected. Under the "needs and preferences theme" gathering information from consumers directly and transforming it to an output which can map to design requirements and technical aspects is one I/O objective. For the "readiness theme" the type of information expected is that which highlights the psychological considerations of consumers, and creating an output which allows firms to make a "go/no go" decision regarding MC for a specific product or market.

Need and preference assessment
Assuming readiness, the MVP modeling method for menu-based scenarios from Liechty and Ramaswamy [6] relies on initial response information from consumers which represents the menu presentation and feature content within menus. That is, it is necessary to perform experiments in order to generate data which leads to a predictive MVP model. The resulting model can be used to establish optimal feature options and pricing structures in the menu scenario for a given objective. Fogliatto and Silveira [8] also gather information from consumers regarding product attributes that is subsequently analyzed using cluster analysis, conjoint analysis based presentations and preference models leading to an output of optimal choice menus.

For the framework provided by Frutos et al. [9] the information exchange occurs between customers, the firm and suppliers. Essential to the process is an approach that fosters knowledge creation and distribution among these three players by bringing the customer into the design process. This work deals within the framework of consumers choosing between a finite number of permutations or altering prescribed components in a limited manner. According to Frutos et al. this integrated knowledge sharing is critical to the success of MC since reliance on consumer expertise in achieving customized goods is not the intent of the paradigm.

Fung et al. [10] elicit consumer's psychological and behavioral responses to product styling using objective
parameters (physical properties) and subjective parameters (appreciation of beauty). From this information, psychological responses to product form lead to behavioral responses (approach or avoid the product). Extensive interviews with consumers are required in order to build this knowledge.

Assessing customer readiness
Moving away from information that speaks to necessary form and function to that which quantifies "readiness" for MC on the customer's part. The "readiness framework" of Bardacki and Whitelock [7] relies on information from the customer base to determine if MC is a desirable paradigm for the particular product, or industry, based on dimensions of "willingness to pay", "willingness to wait" and "willingness to customize". However, the information type necessary for assessing each of these dimensions is not described.

Similarly, in developing the five-level CCS scale, Guilabert and Donthu [11] rely on information from consumers that came through focus groups and pilot and validation studies to develop and confirm the scale. However, there is no application of the proposed scale to validate its applicability in a real product development scenario. In addition, it is unclear how the scale moves along the dimensions of development (e.g. Is it a Likert scale?) and the inclusion of "price" as a key parameter on only one of the scale values seems like a point of ambiguity if the scale is used by firms as an output for decision making.

Obvious in both these themes is that no matter the goal, intimate contact with a large cross-section of individuals representing the market is critical to gathering sufficient information and making decisions regarding the paradigm. This would lend itself to a need for metrics to aid in the information input-output relations in marketing.

3.3 MC METRICS IN THE MARKETING DOMAIN
Maintaining these two themes for MC in the marketing domain identified in Section 3.1, the expectation is to find a number of metrics that would quantify aspects of MC which influence the product design or assess readiness. Instead, what was found is a serious lack of defined metrics that could aid firms in quantifying opportunities and supporting decisions regarding MC on both thematic fronts.

A number of authors mention potential metrics which have been found across the MC literature (and beyond) as a way to map consumer needs/preferences to product form and function. Liechty and Ramaswamy [7] do not specifically identify metrics for MC. However, it is possible that some of the MVP based equations and probability distributions could be used as a basis for a metric that aids product designers. Bardacki and Whitelock [7] mention two specific metrics, lifetime customer value (LCV) and customer customization sensitivity which is a function of demand for innovation AND customer sacrifice gap. However, no specific equations or descriptions for modeling these parameters are introduced.

Though not necessarily MC-specific Frutos et al. [9] look to value derived from multiattribute modeling techniques as a metric. Here, a multi-attribute value function (MAVF) is used to quantify the value of one configuration over another. This metric was chosen over analytical hierarchy process (AHP) because it is more transparent and easily understandable, yet it is important to note that an assumption of this metric is the preferential independence of attributes.

Fung et al. [10] provide definitions for four pleasure types (physio, socio, psycho, ideo) and core parameters that define "pleasurability" (objective parameters that refer to physical product properties and subjective sensations perceived by consumers), no specific manner of quantifying or measuring these parameters are identified. Additionally, it is noted that while objective parameters can be quantified and / or measured, subjective sensations require the use of cognitive psychology.

Moving from metrics which influence design toward those that assess readiness, while the CSS scale developed by Guilabert and Donthu [11] is a metric in itself that could be utilized as a "filter" for assessing the desire for customization in particular markets (or segments) it is necessary that validation studies are conducted to prove the ability for the proposed scale to reliably filter opportunities. The work of Bardacki and Whitelock [7] only presents ideas which could become metrics but provide no description of conveting these ideas to mathematical formulations.

In order for the paradigm to be successful quantifying and validating at the marketing phase is critical to knowing if moving forward with the engineering and distribution is viable. In short the deficiency in metrics for MC within the marketing domain represents a significant challenge to the remainder of the design process. General barriers are described in the following section.

3.4 MC BARRIERS IN THE MARKETING DOMAIN
While both themes emerging from the marketing domain are expected to have barriers in application, it was discovered that those barriers exist on different dimensions.

Need and preference assessment
The literature aimed at mapping consumer needs/preferences to product form and function is most difficult to apply. For instance, the MVP modeling method for menu-based scenarios [6] is heavily research based which may prove a natural barrier to firms. Additionally, applying the method to manufactured products (instead of web services) would add a significant challenge since information regarding pricing and constraints would often be dictated by the technical domains of engineering and distribution. While the method from Fogliatto and Silveira [8] is extensive, the application to a service problem (natural gas) is a limited one that does not begin to highlight the additional challenges faced in the design of manufactured products (e.g. mapping customer attributes to technical attributes). Thus a significant barrier to use seems to be adapting the method to aid in the design of such products for MC.

For the decision support system put forth by Frutos et al.
the major barrier is the tedious and complex nature of assessing the value functions, defining the criteria independence conditions, and comparing several alternatives for several customizable components, even within the graphical framework proposed. A practical application of this decision support system to a real customization process is far from simple.

Fung et al. note that many uncertainties exist when dealing with the creation and identification of a new fashion trend. While design experts may gain the experience necessary to successfully complete this task, gaining this experience can take a considerable amount of time and exposure to various design scenarios.

Assessing customer readiness
On the "readiness" front, Piller and Muller note that in addition to the cost of the firm, there are also two costs to the customer: 1) the premium of the individualized product as compared to a standardized product; and 2) the cost of actively participating in the design of the product. Companies must be able to identify avenues where the willingness to pay is attractive for customization. The work of Barlacki and Whitelock [7] and Guilabert and Donthu [11] highlight the importance of understanding the consumer "customization psychology" in the marketing domain but neither result is ready for application.

Though the work reviewed overall for the marketing domain does not represent an exhaustive list, it is certainly representative of MC efforts in the marketing domain over the last decade. What is most striking is that despite the importance of the consumer in the MC paradigm, the available literature pertaining to the marketing domain appears sparse as shown in Table 1. In this sense, there is significant opportunity for additional research on MC strategies within the marketing domain. These will be highlighted in Section 6. For now, the review moves to the engineering domain.

4. MC AND THE ENGINEERING DOMAIN
While marketing based methods for MC are lacking, one can find a significant amount of literature regarding effective strategies for engineering mass customized goods. However, this seems a bit of a paradox considering that niche market segments are the motivating driver for customized goods. Yet as the previous section shows, there is much research to be done in effectively modeling those segments.

To get around this apparent paradox, the engineering of mass customized goods has relied heavily on the use of modularity and the emergence of product platforms and families [92] to achieve discrete levels of customization. For example, Dell Computers, which is often cited as a successful model of MC, relies on the use of modular computer components to allow menu-driven customization of PCs. Here, customization occurs within the constraints of four to five product families whose core is based upon increasing memory and speed. Creating such a portfolio of products is especially important as research has shown that while initial increases in variety do lead to increased sales, such benefits do not keep pace once variety is increased beyond some threshold. In addition to variety, product platforming has been shown to reduce development time and the risk and complexity of design, allow for responsive introduction of new manufacturing processes, and enhance product lifespan.

To leverage product families across multiple market segments, Meyer and Lehnerd introduced the market segmentation grid, which has led to two approaches for product family design. A top-down approach is used to manage a family of products and their variants when starting with a core product architecture. Conversely, a bottom-up approach permits the redesign or consolidation of a group of distinct products in an effort to standardize components and control costs. Scalable product families, originally required the definition of the platform a priori, however an increasing number of recent works allow for simultaneous platform determination and variable scaling as in [100]. Configurational (modular) product family design focuses on creating variants by adding, interchanging, and/or removing functional components from a modular architecture. Challenges in configurational product family design include module identification, interface standardization, and architecture embodiment. A comprehensive discussion of product platforming fundamentals, and research within the field, can be found in [103, 104].

In reviewing MC relevant literature for the engineering domain, the results show three distinct main themes from a methodology perspective: 1) development of product platforms; 2) creation of product configurators; and 3) a focus on the lifecycle of the product / architecture. The inputs and outputs of these methodological themes serve as driving forces, encompassing the integration of the customer, accounting for the connections between components, and the identification of sources of system change and uncertainty. The subsequent subsections review research efforts that fit these themes in the context of the motivating research questions from Section 1.

4.1 MC METHODS IN THE ENGINEERING DOMAIN
Product platforming
Given the notion of modularity and scalability, it was an expectation to find research focused on the development of product platforms within the engineering domain. Further investigation of this theme led to the emergence of two sub-themes. Papers dealing with product platforms focused on identifying product variants using assumptions about customer preferences and demand, or determined the foundational architecture using engineering information (i.e. connections and interfaces). While not all approaches truly represent MC as defined in this paper - some methodologies require customers to select from a finite set of already constructed variants - many of these approaches can be generalized and extended to the MC paradigm.
Integration of customer voice / demand

One of the first product platforming works to integrate market segmentation with generalized consumer demand models was the Product Platform Concept Exploration Method (PPCEM) [14]. Here, it is required to create a market segmentation grid and then aggregate the product platform specifications while operating under the assumption of uniform demand. Williams et al., [35] built upon this approach by integrating a utility-based comprise decision support problem (DSP) and allowing for the definition of non-uniform demand profiles for different market segments. While this approach is not specifically designed for individual consumers, this methodology offers a means of achieving product variety and allowing for the tradeoff between platform extend and platform performance to be explored.

Zha et al. [21] leverage the Voice of the Customer (VoC), fuzzy set theory and neural networks to determine the optimal module combinations that satisfy customer requirements. Customer preferences are used by Yeh and Wu [23] to identify the cheapest feasible option that meets a customer’s requirements out of a set of feasible candidates. To ensure product functionality, a compatibility check is used to ensure proper interaction between selected modules. The Product Definition and Customization System (PDCS) [18] involves customers in the design process by merging a generic product platform with specific customer-oriented product concept information to develop customizable product platforms. Of all approaches studied in this sub-theme, this methodology satisfies the notion of MC the most, potentially standing in opposition to Hypothesis 1.

Architecture definition

Many approaches that deal with defining the architecture of the product platform are intended for generalized product design rather than MC. However, while the implications of these methodologies are not often stated by the authors, modularity is an inherent aspect of MC. Yu et al. [55] present a clustering technique using Design Structure Matrices (DSMs) to visualize product architecture. Products are partitioned so that interactions within modules are maximized and interactions outside the module are minimized. Dendrograms are used in [40] to visually quantify the degree of commonality in a module when only the requirements are known and the architecture has been determined. Commonality measures are also used by Jiao and Tseng [24] to compare possible product family solutions, while Hofer and Halman [44] study component layout.

Gonzalez-Zugasti et al. [41] move beyond visual cues and introduce a two-step process toward designing product families. The first step deals with the technical aspects of the family - optimizing around a set of objectives subject to technical constraints when external uncertain factors are fixed. External uncertain factors are considered in the second step, where the value of each identified design alternative with respect to the producer is quantified. Real options concepts are introduced to delay risks that occur during product development due to uncertainty in technologies and funding. This allows for value to be viewed as the sum of the benefits minus the investments necessary to develop and market the product. Tseng and Chen [31] use a binary-tree algorithm to configure a product using three types of constraints: 1) customer needs; 2) essential and optional parts in the product configuration; and 3) dependence and mutually exclusive relationships among product parts. Constraint analysis is also used by Corbett and Rosen [46] to identify potential configurations of a product family, while a three-step analysis approach is introduced by Gao et al. [17] to determine the values of the platform parameters.

Product configurators

Product configurators go beyond integrating customer preferences by actively involving customers in the process of design. Works by Siddique [14, 23, 26] discuss the need for tools that are capable of collecting customer requirements, transforming them into product parameters and options, and then checking the engineering and economic feasibility of the proposed design. Specifically, they outline a CAD/FEA/Optimization web-based template capable of doing this. Specifically, two grammars are used: product variety space grammar and product variety model grammar. If initial optimization approaches fail for the initial design, users are asked to pick categories that can be relaxed to find a feasible design. Overall, this framework allows users to select a set of options, determines a feasible design, and then displays a solid model of the product along with additional information. Huang et al [32] and Simpson et al. [33] present an information infrastructure framework for developing and applying online Web services specifically for MC and platform product development. This idea is also adopted by Franke et al. [54], who propose the use of peer designs as a starting point for new users so that they have help identifying potential solutions. Finally, Lu et al. [28] describe the development of an intelligent system for custom clothes that use body dimensions, clothing pattern generation and fabric cutting.

Du et al. [45], [26] use graph grammars and graph rewriting as a means of modeling product family design from both the sales and engineering perspective. Customer requirements are transformed using product rules to generate products. These graph grammars allow for attaching, removing, swapping, and scaling. Finally, a key risk of customer involvement in MC occurs when customers become overwhelmed, or confused, by the large number of available options. Chen and Wang [19] address this concern by developing personalized configuration rules (PCRs) that attempt to remove the knowledge gap between customers, salesmen, and designers.

Lifecycle-focus

A primary challenge associated with MC is understanding the impact of component change on system performance and subsystem interactions. Such changes are integral to meeting the need of individualized consumers and extending the lifecycle of a product. In this light, Eckert et al. [38] explore the best
approach to changing a system when it cannot be avoided. They discuss how component changes rarely occur alone and often impact other components. Such uncertainties also exist throughout the scope of a product's lifecycle. Suh et al. [16] present a platform design process that accounts for uncertain variant demand and specification changes. Their hypothesis is that if the right subset of elements is designed with flexibility, the resultant platform will be more nimble in the future and able to avoid expensive redesigns and manufacturing switching costs. Martin and Ishii [15] strive to reduce development costs using a modified QFD structure to meet the uncertainty in future customer needs, technology changes, and competitor responses. This is accomplished by engineering teams using their expertise and judgment to estimate the cost of changing a component to meet the most stringent future targets. Finally, Customer Value Chain Analysis [42] enables design teams to comprehensively identify pertinent stakeholders, their relationships with each other, and their role in the product's lifecycle during the product definition phase. This supports the decision making process by 1) confirming the product's business model; 2) recognizing the critical stakeholders; and 3) clarifying the value proposition to be embedded in the product.

Together, these three themes focus on creating architectures that can be used to increase variety, allow for responsive change, and can meet future uncertainties. The next section investigates the information flows for these approaches.

4.2 MC INFO I/O IN THE ENGINEERING DOMAIN

To facilitate the three themes identified in the previous section, the information flow in and out of the methodologies can also be segmented into three groups.

Customer integration

Within the engineering domain, customer integration takes on two forms. Some methodologies rely on the use of market segmentation grids to understand the wants and needs of the consumer. In these cases, the heterogeneous preferences of consumers are grouped into clusters, and decisions on platform components are typically made by engineers. Other approaches actively involve the customers in the design process. Here, the customer determines the form and functionality of the product while engineers ensure availability and system feasibility.

Market segmentation

Simpson et al. [14] first proposed aggregating product platform specifications using information from the market segmentation grid. By modeling the constraints and "goals" for the product platform, manual investigation of potential solutions allows for the determination of which variables should be part of the product platform. Williams et al. [35] built upon this work by using a multi-attribute utility function constructed by assigning a utility function to each design objective. The authors discuss exploring the space of customization by analyzing demand; however this paper does not explicitly address any of these tasks in great detail.

Other approaches use a combination of customer requirements, market trends, and/or demand information [44, 21] as a means of determining module layout. Dondaldson et al. [42] states that understanding customer values involves addressing compliance issues, user needs, competitive product analysis, and localization considerations. This information is then evaluated relative to the design team's corporate strategy. Arrows are used to signify how customers are related to the product, and to each other. Chen et al. [18] propose perhaps the most comprehensive strategy, using a "laddering technique" to understand and group customer needs using conjoint analysis. The result is a "design knowledge hierarchy" which aids designers in creating appropriately platformed concepts that can be customized later.

Customer involvement

Approaches that involve the customer generally require an individual's preferences and the potential options that a company can offer. Additionally, a company must also identify all the change rules and how to manufacture the system [23, 26]; creating an environment where engineers provide the potential options and consumers pick the final configuration. Chen and Wang [19] require customers to input personal characteristics into a web-based system, which then suggests the appropriate configuration. In a web process developed by Ninan and Siddique [13], consumers specify dimensions, material selections, and optional modules. This information is then passed to CAD and FEA modules and integrated within an optimization routine. A web-based system is also used in [22] to facilitate option selection, and a set of graph grammars is then used to convert this information into a solid model with the necessary assembly steps. Lu et al. [28] go beyond a web-based system, using 3D body scans and 2D photos to determine dimensioning for custom clothing. Resultant CAD models are compatible with CNC laser-cutting machines.

Component connections / modularity

From a graphical perspective, Du et al. [36] rely on graph grammars as a means of organizing product family elements in terms of commonality and modularity. Alone, this approach is not enough to achieve MC as it is designed to contain the unmanageable amount of information that would be created if Bills of Material were created for each variant. Hollta-Otto et al. [40] use dendrograms to look at function inputs and outputs. Module similarity is then compared by looking at the physical properties of the module interfaces.

Considering the physical aspect of module design, [46] relies on the input of components, functions, component-functionality mappings, interfaces, and assembly sequences. Beyond these inputs, Jiao and Tseng [24] state that product family members must be designed with enough detail to estimate costs and run size. Component information is also required by Martin and Ishii [15], who develop a coupling index by considering the "specification flows" among components. To generate the coupling index for a product, the
basic technology to be used and the general layout of the product must be known. Additionally, the design team must estimate the sensitivity of components to small specification changes to minimize the need for major redesign efforts later.

**Sources of uncertainty**

The notion of component coupling is investigated by Eckert et al. [38], who identify two types of changes that can occur within an architecture. Suh and de Weck [16] assume that preliminary platform designs have been developed and that all variants come from the original platform. Multiplier elements, elements that as more changes are added make the system harder to change, are identified as prime candidates for incorporating flexibility. Gonzalez-Zugasti et al. [41] considers endogenous (design risks or outcomes of tests during development) and exogenous factors (funding changes, market acceptance of product, competition) of uncertainty. A rolled uncertainty analysis is applied to evaluate expected risks, performance, and costs, and their sources. Uncertainty here is not due to designer preference uncertainty, but uncontrollable factors during product development and operation. Yu et al. [55] move beyond product consideration and investigate the interactions between development team members to arrive at a more sensible arrangement of "who is talking to whom, about what, and how frequently."

### 4.3 MC METRICS IN THE ENGINEERING DOMAIN

Metrics within the engineering domain are found in only a small subset of the reviewed papers, and tend to be generic without detailed formulation. While a few metrics focus on quantifying how well the desired product meets the needs of the consumer, others are created to assess the commonality of the modules in the product family.

**Performance-based**

Performance-based metrics in the literature attempt to explore how customer requirements can yield the "best" product platform. Complex equations have been combined with fuzzy sets to capture requirements that represent product attributes (very low, fairly high, etc.) [21]. Williams et al. [35] presents a multi-attribute utility function that is the combination of multiple performance criteria to aid in determining the "best" product platform. Additionally, Franke et al. [54] talk about preference fit, willingness to pay, and purchase intention as a means of evaluating consumer designs and examining how close a consumer gets to their actual preferences.

**Commonality / modularity**

Jiao and Tseng [24] introduce the component part commonality index (price, quantity, family members that use a part, unique parts, etc.) and the process commonality index (number of processes to produce a family, assembly processes used, manufacturing processes used, whether a process is unique or could be used to make multiple parts, lot size, and setup time). These are information intensive and must be done at the end (or close to) detailed design where changes are incredibly expensive. Using the concept of specification "flows" within a product development project, the design for variety (DFV) method [15] provides two indices to measure a product's architecture: (1) the generational variety index (GVI) is a measure for the amount of redesign effort required for future designs of the product; (2) coupling index (CI) measures the coupling among the product components. Finally, [40] uses graphical approaches and ratio scales to mathematically calculate the similarity of two modules by using dendrograms.

### 4.4 MC BARRIERS IN THE ENGINEERING DOMAIN

Barriers toward achieving MC in the engineering domain stem from challenges in gathering and effectively using marketing information, determining the proper composition and performance of the desired products, and maintaining flexibility within design teams. From a marketing perspective, an obvious barrier (that even goes beyond MC) is the need to accurately define market segments [44, 33]. However, a challenge unique to MC is that customers must have knowledge of the product in order to properly establish their preferences and customize it [23]. Without an accurate knowledge of market demand, a producer is unable to determine the appropriate extent for managing variety, and many approaches in product platforming do not approach commonality decisions with a systematic process [35]. Yet, producers are required to identify a product family, and what it should be able to achieve a priori, giving the customer a choice set with which to customize [45, 22].

Determining the appropriate number and configuration of modules requires a large amount of information to be gathered, analyzed, and stored [46, 21, 24]. Advances such as graph grammars [36] provide necessary data modeling support, but are not intended to replace the under-developed decision-making process associated with variant design. An additional difficulty arises when assumptions are made that exact connections exist between consumer needs and functional requirements, and that historical data relating these two is available [19]. To combat this, producers often relax performance constraints to arrive at a feasible product, which may lead to a loss of value (i.e. the customer no longer gets what they really want) [25].

Managing value losses requires the ability to negotiate with customers on requirements. Eckert et al. [38] note that this requires a producer to employ people who have technical training, but who are not involved in the day to day design activities. Furthermore, the decision making process will also involve negotiations between different sub-systems over tradeoffs in solution strategies. Such a requirement for communication between product development teams can be impossible to implement if a proper infrastructure is not established [55]. In cases where teams can communicate, making such tradeoffs require that change rules, and how the product will actually undergo the change, be extensively identified [26]. However, difficulty also exists in relating costs to product performance, particularly during the early stages of
the design, when little detailed information is known about the final product, its means of production, or its associated manufacturing and inventory costs.

5. MC AND THE DISTRIBUTION DOMAIN
Manufacturing of goods includes fabrication and assembly of parts from suppliers. Generally speaking, more complex products increase the size of the supplier network leveraged to manufacture a good. It seems logical that more suppliers would lead to an increase in variety which is ideal for MC. However, the increased stress of managing information flows, communication channels and demand uncertainty among suppliers makes it economically infeasible to manage MC in the design of many complex products. This is best exemplified in the manufacture of automobiles where Alford et al. [86] point out that customization through options packages is the only viable MC approach given the challenges in managing the supply chain and delivery of vehicles.

Even in products that are not overly complex, meeting the customization requirements of consumers in many cases could require the need for extended lead times that push back product delivery dates. If a consumer walks into a store looking to customize AND purchase a good at that moment the customization approaches and options are limited. For example, imagine if a consumer wants to purchase a cell phone but would like to customize the software and case geometry and walk out of the store with the phone. Outside of pre-determined options set during the design phase such a purchasing scenario is not possible today. This is not due to a lack of manufacturing and information technology however - it could be possible to rapid prototype [67] a cell casing based on 3D scan data of the individual and customize the software in the store. Rather, integration of these “on site fabrication” and delivery enabling technologies has yet to be explored extensively.

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. Further, the need to deliver products as quickly as possible limits fabrication options.

The emergent themes from review of literature pertinent to the distribution domain are fabrication and assembly of products, and developing methods to handle consumer interaction tasks at the time of purchase. Each of these themes is explored in the context of the overarching questions in subsequent subsections.

5.1 MC METHODS FOR THE DISTRIBUTION DOMAIN
Fabrication and assembly
The fundamental objective generally addressed in fabrication and assembly operations is determination and optimization of the supplier network, typically in a way that can maximize response time. In addition, management of modular inventories and effective use of manufacturing technologies in an "agile" or "flexible" manner is critical to meeting variety needs while maintaining costs similar to mass production levels.

Partanen and Haapasalo [34] present a process for “fast production” of customized electronics in a Swedish firm which relies on modularization of components and delaying the "order penetration point" (i.e. postponing the point in the production process when a product is reserved for a specific customer) in a way to speed the “build to order” or “assemble to order” customization strategy. Similarly, though Waller [39] does not exactly propose a methodology, he does discuss the structural underpinnings of a “build to order” methodology to promote MC in the automotive industry. The method would rely on pushing production dates closer to the dates when capacity is determined.

Yao and Liu [35] develop an optimization model to relieve the contradictory objectives of scale production and customer satisfaction level for smaller consumer segments that MC looks to serve. The optimization model introduces four objectives representing customized cost, delivery date, scale production effect and profits to determine the optimal implementation of the supply chain schedule. A similar notion is discussed by Barnett et al. who describe a methodology to manage tradeoffs between large numbers of small batch production in shoe customization [40]. The key is using IT to improve information access and ease constraints.

Jiao et al. discuss integrated product and production data management for MC production characterized by high variety [38]. Their efforts are focused on development of a data structure set to unify BOMs (bill of materials) and routing to facilitate better production planning and control, order processing, and engineering change control. The resulting BOMO (bill of materials and operations) results from combining the individual BOM and BOO (bill of operations) structures into a single one, integrating product structure data and operations information. Jiao et al. point out that in MC applications a tool like BOMO is critical to handling production characterized by small quantities, short life cycles and high diversity, and the resulting engineering changes leading large numbers of trivial BOM changes for various customized product variants.

Ni et al. develop a QFD based method that leads to the ideal selection of suppliers for products, and a case study demonstrates the method in the automotive industry [41]. For agile manufacturing setups, Zangiacomi et al. introduce a planning and scheduling module applied to the prototype of a new factory or agile production unit [44]. Yao and Carlson [64] focus on agile manufacturing setups for custom furniture production and find that lot size is a critical parameter to control in striking a balance between reasonable production costs and ability to manufacture. They suggest that separate facilities focused on production of mass customized products may be necessary if the paradigm is to be successful for some firms and industries.
Consumer interaction
Consumer interaction in the distribution phase of MC is primarily focused on aiding consumers in one of two ways. The first represents directing consumers to most appropriate options in customization strategies where vast numbers of options are the approach to providing adequate variety to be considered "custom". The other focus is the creation of "configurators"; internet driven applications which allow consumers to select among components or subsystems in building a customized product.

As an example of "recommendation systems", Zhang and Jiao propose an associative classification-based recommendation system for personalization in B2C e-commerce applications [71]. This system supports personalization by helping customers find the products they would like to purchase among overwhelming amounts of information and product options.

In terms of "configurators" Ma et al. propose online product customization and a web service-oriented approach where users can source competitive offers and generate feature-based CAD models from different vendors over the internet [37]. The service gives the user the opportunity to visualize results in the design space and create standard component modules without the limitation of predefined templates. Access to catalogs from multiple suppliers provides wide variety.

A more advanced concept of product configurator is represented by the work of Bateman and Chang who introduce devolved manufacturing [65]. By 'outsourcing' the design and configuration of the product, along with attendant costs for time, computing, internet and phone line usage to the customer, the manufacturer effectively becomes involved only when there is something for the manufacturer to build [65]. The devolved manufacturing approach will add another layer of complexity, that of ‘design for customization’. Much consideration will need to be given to defining 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.

These approaches, while reinforcing the use of product platforms in design, also create challenges in information flow since the distribution phase must manage internal production information and consumer input that dictates production and delivery. The information flows are discussed next.

5.2 MC INFO I/O IN THE DISTRIBUTION DOMAIN
Fabrication and assembly
Typical of production processes the information inputs for fabrication and assembly activities must lead to outputs which detail the components and processes necessary to create the final good. Perhaps the most critical difference in the MC paradigm is the timing of this information. For instance, the methodology from Partanen and Haapasalo requires information input from the consumer at the point of manufacturing (think Dell) - recall the need to delay the order penetration point - which requires the product architecture to be largely the same for most consumers to decrease lead time [34]. The information output is the component modules which should be pulled and utilized at the point of assembly in order to allow some level of customization. There is a very limited level of product variety which can be served through info coming this late in the process unless niche market profiles are created in advance of the engineering design.

The work of Waller, while inherently requiring postponement in the order penetration point also points to demand volatility as the critical input to any methodology for MC in the automotive industry [39]. Specifically quantifying and reducing the uncertainty is important to the success in customization of vehicles.

The S3 methodology from Barnett et al. [40] demonstrates however that an appropriate combination of IT capability and ideal lot sizes can provide for more customization capability while still meeting reasonable production time lines in the production of custom shoes. The method requires information exchange between key members - Factory Planner (FP) and Team-based Schedulers (TBS) - where FP interacts with consumers and feeds customer orders to TBS and TBS outputs delivery dates to FP. Zangiacomi et al. - who deal in custom shoes as well [44] - also demonstrate the possibilities for MC production when planning is done with the help of an order process system (OPS) software which is completely configurable to user needs. Their developed OPS tool draws consumer information and then ranks orders based on priority values which dictate scheduling.

In striving for economies of scale in production, information from a multitude of sources is necessary. The methodology of Yao and Liu represented in the four objectives that serve as a basis for their approach provide an excellent example of the type and processing of information that necessary in MC production decisions as the approach draws on information from multiple disciplines within the firm and from the consumer [35]. The information represents economic parameters and preferences (utilities) to explore tradeoffs in the key contradictions of consumer satisfaction and economies of scale.

Similarly Ni et al. [41] focus on converting customer requirements into product characteristics and deploying requirements for the manufacturing process by leveraging data mining techniques to improve upon the limitations of data collection in traditional QFD. Like work in [35] the advanced QFD approach requires information from a multitude of sources in the product's full life-cycle, such as maintenance records, customer data, and information on market segments.

Consumer Interaction
Few web service applications are available for CAD collaborations. Ma et al. [37] develop a reference architecture
for electronic catalogues in order to provide flexible feature-based CAD models in online product customization systems. Zhang and Jiao [71] work towards gaining information from customers in order to customize the product through e-commerce, leveraging knowledge discovery and data mining to filter consumer information - specifically, semantic data - and offer most appropriate products to fit their needs.

Bruce et al. [72] state the need to identify channel parameters of different launch areas (competition, distributors, etc.), identify relevant cultural mores (holidays, individualistic versus communal societies, etc.), determine language and colloquialism differences (Fish & Chips versus Fish & Fries), and determine variations in technology infrastructure.

The breadth and challenge in handling information across these distribution themes present motivation for metrics that aid in managing the information. However, as the next section shows this motivation has not led to many metrics.

5.3 MC METRICS IN THE DISTRIBUTION DOMAIN

Few metrics emerged from the literature review from either theme. Of note, Zhang and Efsthathiou use complexity - defined as a function of number in inventory and assembly lines, number of variants and batch sizes - as a metric to quantify aspects of distribution under various MC strategies [80]. The intention is to reduce complexity by addressing the variable that has the biggest impact on complexity for the given customization strategy. While they provide the concept of complexity as a metric, there is no specific equation provided. In the criteria configuration module from Zangiacomi et al. [44] 12 selected criteria play a key role to quantify priorities. These are divided into 4 categories: 1) urgency; 2) complexity; 3) profitability; 4) importance. This however, represents the extent of metric discussion found in the literature review.

5.4 MC BARRIERS IN THE DISTRIBUTION DOMAIN

Barriers to implementation within the distribution activities of MC are focused in the fabrication and assembly activities. The specific barriers can be categorized as issues of complexity or issues of organizational culture.

For example, the algorithm from Yao and Liu [35] 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, though Waller's [39] review is extensive and highlights the five most critical factors - speed, simplicity, certainty, visibility, and clarity (all of which could potentially be MC specific metrics) - the critical barrier in implementation is the current approach to automotive manufacturing. 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, for Barnett et al. [40] a key takeaway 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 as successfully demonstrated in the 3S method [40].

6. CONCLUSIONS FOR MC MOVING FORWARD

Though the literature sources are not an exhaustive list, the specific issues raised in Sections 3-5 are representative of the state-of-the-art in MC as it pertains to engineering design. Based on the overall review of literature in the three domains a number of conclusions can be drawn, specifically in the context of the MC definition presented in Section 1. These conclusions are presented here with suggestions for moving forward and are intended to outline areas for future work.

From the marketing domain results, the limited volume of research in this area demonstrates that there is a greater need for methods that are focused on assessing needs and preferences in the context of MC. This supports Hypothesis 1 presented in Section 1. In moving forward with the MC paradigm it is apparent that greater focus on the marketing domain is critical. Essentially, there is a need to develop tools and methodologies that allow consumer needs and preferences to be understood at a level discrete enough to support true MC. By "true customization" it is implied that the core architecture of a product capable of supporting MC is not engineered until after a well defined market portfolio is established. It should be noted that there are research efforts focused on preference modeling and mapping in the engineering design domain which is increasingly focused on understanding heterogeneity in consumer preferences [105-108]. Tailoring these emerging methods to MC may be a viable approach that could have immediate impact on the paradigm.

Further, as seen in Table 2 there are few literature sources that fit a "total process" classification. This identifies the need for research and methods to aid in the transfer of information at the marketing-engineering and engineering-distribution domain interfaces as stated in Hypothesis 2. Further within those works and even within the domain specific literature, little time is spent focusing on the type and form of information and its exchange. Yet, managing information is expected to be one of the most critical aspects of any successful MC methodology [109].

An additional finding from a review of the marketing domain is the need to investigate customer readiness for MC. This is a critical aspect for firms to consider as it may influence both the decision on whether or not to pursue MC in the first place and the amount and approach to customization to be utilized. Looking at "success factors" for MC as suggested by [109] could support this understanding from the consumer perspective and beyond. Customer readiness in itself is a natural barrier to the MC of any product and must be quantified before any implementation.
In an engineering context, most attempts at achieving a mass customizable system rely on modular design or a core architecture from a product platform. To produce a finite choice set for customers to work with, engineers are required to identify system modules – or the architecture of the product family – and what they should be able to achieve a priori. However, most papers dealing with product platforms tend to focus on identifying variant designs using extreme simplifications about customer preferences and demand, or determine the foundational architecture strictly from engineering knowledge about connections and interfaces. Without an accurate model and understanding of market demand, designers will be unable to determine the appropriate extent for managing variety. If too many variants are created, customer involvement can suffer if customers become overwhelmed or confused by the large number of available options. If too few variants are created, the performance sacrifice may force a consumer to choose an outside good. Further investigations into simultaneous market segmentation and product variant creation are necessary to maximize customization approaches.

MC fundamentally involves the customer in the design process. When customers determine the form and functionality of the product by choosing from the available modules and components, engineers must ensure component availability and overall system feasibility. To do this, however, customers must have knowledge of the product, and understand the impact of proposed changes, in order to properly establish their preferences and be actively involved in the customization. For this paradigm to mature, there is an immediate need for elicitation methods and configuration mechanisms that support customization without overwhelming the consumer with options.

Few metrics for MC exist in the engineering domain; and those that do tend to be generic or without detailed formulation/application. While metrics created to assess the commonality of components in a product architecture have been developed and tested, there is a need for research efforts in quantifying how well the desired product meets the need of each consumer. Furthermore, information regarding customer sensitivity to price in MC need to be further explored.

Within the distribution domain it is clear that the technologies (e.g. rapid prototyping) and agile manufacturing approaches are maturing to a level where accommodating significant variation between products is feasible as long as the appropriate IT infrastructure is in place. The fundamental challenge to this aspect of MC lies in finding the appropriate mechanisms for guiding consumers through the ordering and customization process. This includes identification of optimal product configurators that aid consumers in selection of components for overall customization. Understanding issues related to ideal presentation of products (i.e. by attribute or alternative) [110], ensuring that the customization process is not time consuming due to "superfluous flexibility" [111] and that fabrication processes can deliver the custom good in acceptable time frames [7] are crucial to distribution domain success. This implies that strong consideration must be given to the cyclical nature of the MC product life cycle in as much as “market assessment” (part of the marketing domain) and "selling" (part of the distribution domain) will influence one another through the configurator mechanism.

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 six critical questions across three categorical “domains” the literature review presented here has highlighted a number of emergent themes in MC. In addition it has identified some critical areas for design research to explore and develop. While we, like Zipkin, believe 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. We are hopeful that this work provides a useful, current perspective on MC and serves as to highlight areas for new and continued progress in the paradigm.

REFERENCES


