DESIGN METHOD SELECTION TO SATISFY CONSUMER VARIATION: A META-DESIGN APPROACH

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ABSTRACT

Scientific fields typically have meta-heuristics that help scientists select appropriate modeling, analysis, or testing procedures based on problem parameters. For instance, the Reynolds number calculation dictates to fluid dynamicists the classification of the flow and subsequent modeling and analysis tools most appropriate to use. As engineering design matures into a field defined by scientific principles, there is a need for similar meta-heuristics to help designers select appropriate design tools and methods. There has been significant work developing design methods to support product development including robust design, product platforms, and reconfigurable design, among others. Many of these methods have matured into design paradigms but are still undergoing validation, exercise, and extension. However, when faced with a new product design (or re-design) problem, it is a challenging task to determine what methods or paradigms to subscribe to and implement; part of this decision involves whether to design a single product or a set of similar products (i.e., a product line). This is fundamentally a meta-design problem – the design of the design method. This paper proposes an approach to support this meta-design decision using market segmentation data and appropriate contextual information.

1.0 INTRODUCTION AND MOTIVATION

There are numerous tools that have been developed to facilitate the different tasks involved in the design of a product or product line, with contributions coming from marketing, engineering, and manufacturing. The overarching goal of these tools is not only to design more effective products, more efficiently, but to make the design process more scientific. To do this researchers have looked to identify principles and theories which can be validated, then applied to the design of new systems; this serves to expand the science of design [1]. Previous work has also investigated the design of the design process, denoted in some work as meta-design [2]. Part of the challenge of meta-design is considering issues in the design of the product, while designing the process.

Numerous books have been written concerning the engineering design process [3-7], describing the steps of the design process and the flow of information between these steps. Identifying the steps in a design process allows it to be completed systematically. Designers have also recognized that there are a number of ways their systems can satisfy requirements. This observation led to the development of design methodologies which are independent of the design process followed. For example, Product Family and Product Platform concepts focus on how component commonality amongst systems can be leveraged while providing differentiation in product offerings [8]. The development of design process models and design methodologies has led to the development of an extensive set of design tools; [9] provides an overview of a representative amount from over two hundred publications.

Design tools have looked at methods which improve the efficiency of the design process, transferal and representation of information, and the measurement of the success of the design process. For instance, Decision Based Design research focuses on bringing a sense of rigor to the variety of decisions engineering designers make in a design process [10]. Functional modeling is used to represent systems as a network of functions and subfunctions [11]. Commonality metrics have been developed so design firms can measure how successful their product platforming efforts are [12-14]. With the vast number of design tools available, and multiple design
methodologies that can be implemented, a question that needs to be answered is how can a design firm determine what design methodology should be used for a given design problem? This question becomes harder to answer when there is a wide range of consumer needs, which may lead to multiple market segments.

When multiple segments exist, companies have several options: they can take a robust design approach, designing one product to fit all the segments [6]; they can create a product family, generating one or more variants for each segment [8]; a (re)configurable system can be developed, which would be adapted to fit different segments; a mass customization approach can be developed; or a combination of these opportunities can be investigated [15]. Which of these methodologies is used can have a significant impact on the success of the product(s); while consumer variation may often require a line of products to adequately fulfill consumer needs, there may be instances where a single system is adequate, required, or preferred.

While a large amount of design process research has been conducted, there is a lack of work investigating how the different design tools can be used and integrated to identify a viable design methodology to address consumer variation through the design of one or more products. This is essentially a meta-design problem and one that must be addressed to further design as a science. Meta-level approaches are found in a number of scientific fields, as shown in Table 1, including some for engineering design. While not necessarily termed “meta-design” in these fields, the process of evaluating key parameters in order to determine an appropriate analysis, treatment, or modeling approach is common. That is, the information is gathered, evaluated with a metric, and a decision is made regarding how the process at hand should be completed.

Consider diagnostic medicine where there are observable and measureable immediate characteristics such as body temperature, blood pressure, chemical levels, etc. The general condition of the patient and their history is known as well (e.g., are they diabetic, obese, generally healthy). The symptoms combined with the patient information are used to form a list of possible ailments, which are then tested in a process known as differential diagnosis. The combinations of conditions have been correlated to indicate what response should be taken, and this is validated with testing. That is, information is used to determine a course of treatment most likely to successfully treat the ailment. Utility theory has been used to improve a similar high-level assessment procedure which is routinely performed in an emergency department to prioritize patients who each require immediate attention [16].

While medicine has a well established meta-level decision process, a number of engineering sciences do as well. Thermal and fluid scientists have established tools and procedures for measuring flow characteristics in order to determine the most appropriate class of analysis models to use. Manufacturing engineers have guidelines and procedures for determining which production methods should be used based on production, surface finish, and tolerance requirements, among others [17]. Early product development currently has a lot of tools, but a meta-design method for determining the best design methodology to handle consumer variation is still largely undeveloped. This is a nontrivial decision that influences the organization’s success.

In early product design there are measurable characteristics which fall primarily into two categories: market information and system information. Market information includes such characteristics as number of segments, variation within segments, and percent of total users. Examples of system information that can be obtained include how integral the product architecture is, what the rough dimensions of the components and product envelope are, and general performance characteristics. This paper begins to develop the mapping of measurable market and system characteristics to design process methodologies by using existing design process tools, while identifying areas where additional decision metrics are required.

This paper begins with a review of current research, looking at the specific design paradigms, marketing tools, and early design process tools. Factors influencing the design methodology are then discussed. Following this, a meta-design method is then proposed and demonstrated on a case study. The paper concludes with method observations and recommendations for future work.

### TABLE 1: COMPARISON OF SCIENTIFIC FIELDS

<table>
<thead>
<tr>
<th>Discipline or Field</th>
<th>Observable &amp; Measurable Information</th>
<th>Information Acquisition Methods</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medicine</td>
<td>Patient History, Body Temp, Blood Pressure, Sodium Level, etc.</td>
<td>Measurement, Testing, Observation, Surveys</td>
<td>Pneumonia Severity Index, Well’s Criteria for Pulmonary Embolism, Emergency Severity Index</td>
</tr>
<tr>
<td>Fluid &amp; Thermal Sciences</td>
<td>Fluid &amp; Material Characteristics, Body Shape, Temperature, etc.</td>
<td>Measurement, Testing, Observation</td>
<td>Reynolds Number, Rayleigh Number, Nusselt Number, Prandtl Number</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Lot Size, Required Tolerances, Material Properties, Shape, etc.</td>
<td>Measurement, Testing, Observation, Forecasting</td>
<td>Adjusted Part Cost, Economic Order Quantity</td>
</tr>
<tr>
<td>Engineering Design</td>
<td>User Needs, System Characteristics, System Performance, etc.</td>
<td>Measurement, Testing, Observation, Surveys</td>
<td>Commonality Indices, Expected Utility</td>
</tr>
</tbody>
</table>

### 2.0 PREVIOUS RESEARCH

This section identifies previous research that is leveraged in developing a procedure for determining what approach should be used for a given design task. The primary contribution of this work is to develop a method which integrates marketing tools with the early design process tools and design paradigms that currently exist to identify which paradigm is best (i.e. product platform, (re)configurable system, etc.). Additionally, areas where more research is required are identified.

### 2.1 Market Segmentation

A product’s success is based on numerous factors: How much does it cost? How is it distributed? What functions can it...
perform, and how well can it perform these functions? What does it look like? These questions point to consumer needs for the consumption chain. “Consumer need” is used generically to refer to preferences and requirements concerning product attributes such as functionality, performance, geometry, aesthetics, mass, etc. The desired value for a consumer need may be a discrete choice (e.g., color), a value (e.g., length), a range of values (e.g., set of gear ratios), or a Boolean choice (e.g., presence/absence of a function). Each individual consumer has a unique set of needs that corresponds to these questions listed. The degree of variation of these needs has implications on how a design firm should approach the development of the system(s). The formal way to examine the differences in consumer needs is through segmentation.

Market segmentation “consists of viewing a heterogeneous market as a number of smaller homogeneous markets in response to differing product preferences among important market segments” [18]. However, how homogeneous segments are varies, and the variation within segments needs to be considered. Market segmentation can be used to refer to segmenting the users for a marketing campaign or for product requirements; this work is concerned primarily with the latter. Market segmentation can be broken into two main components: the “gathering process,” where potential users are assembled together and the “commonalities in specific characteristics” which are used as a basis for the clustering [19]. Several methods have been developed for performing the “gathering process,” and numerous “characteristics” are available to use as a basis for segmentation, which are discussed next.

Demographics provide one method of segmenting users. Demographic information includes such factors as age, marital status, stage in the family and household life cycle, income, geographic information, etc. Demographics influence consumer needs, but are not the sole driver of them. Further, there will always be exceptions to users not wanting a product geared towards their demographic. Psychographics may have a better chance of capturing the softer consumer needs, as they take attitude into account.

Psychographics take into account such factors as lifestyle, activities, interests, beliefs, and motivations [20]. The goal is to capture the softer information that influences consumer needs. While psychographic information points out important factors that are related to customer needs, there are two main problems. First, the accuracy and stability of psychographics varies from user to user [21]. If used solely as the method of segmentation the list of consumer needs would be incomplete.

Demographics and psychographics drive consumer needs, but are not encompassing of all the driving factors. Occasion based segmentation is a recent marketing development, and it studies how the circumstances of use affect consumer needs [22]. All of these factors work together to influence the consumer needs for a system.

Segmenting first on needs and then looking at additional factors will generally lead to better defined segments [23]. Consumer need information can be uncovered from a variety of available methods: surveys, focus groups, consumer feedback, and empathic studies represent a subset of the available methods; best practice suggests that multiple methods be used to overcome individual shortcomings. Once these needs have been captured for a sample of the target users, segmentation can be done based on consumer needs.

One of the methods used in segmenting the market is Latent Segmentation Models. The general concept is that the data is viewed as a mixture of various distributions, which can be determined through statistical analysis. These models determine the segments through iteration and quality of fit. Consumers then fall somewhere in one of the distributions (segments), and have a strength of fit associated with them. The benefit of these models is that how the data should be segmented does not have to be known a priori; this is determined by the model. Disadvantages to using the approach are the analysis is complicated to perform (commercial programs are available), it can be sensitive to extreme outliers, and an optimal clustering is not guaranteed (dependent upon starting point) [24]. Another method of segmentation is to use an Artificial Neural Network.

Artificial Neural Networks (ANNs) have been used to segment the market, with the Kohonen Self-Organizing Map being identified as one of the better known methods [22]. ANNs help with clustering by taking a number of factors and reducing them down to a more manageable level. However, the use of ANNs presents several difficulties: a relatively large data set is required to train them; there must be a know relationship between the initial factors and the reduced factors of the training set; an additional amount of data, also with a known mapping, is needed to validate the model [25]. There are numerous other methods for segmentation, and hybrids can be developed as well. Methods which produce the variance for the different segments offer additional information which can be used later to assist with decision making. Once segmentation is complete, the conceptual design of the system(s) can begin; this is where early design process tools are leveraged.

### 2.2 Early Design Process Tools

Several tools have been developed which can be used early in the design process. Some of these are product representation tools, while others assist with design decisions. Quality Function Deployment (QFD) starts with the voice of the customer and systematically progresses to manufacturing decisions through the use of a fundamental tool called the House of Quality (HoQ) [26]. The HoQ maps consumer attributes, such as “heat quickly,” to engineering characteristics, such as “BTU per hour.” Performance requirements for these engineering characteristics can then be estimated. Pugh extends QFD by adding additional stages to determine technical requirements for subsystems [5]. However, research has identified several limitations to the HoQ.

In [27], the quality of quantitative analysis with the HoQ is placed under scrutiny, while the value of using it as a
qualitative planning tool is acknowledged. However, the HoQ lumps users into one house, and multiple houses would be needed to design a family of products. However, individuals are still being lumped into one house, which assumes the market segment is reasonably homogeneous. Finally, the HoQ evaluates customer attributes; there is no direct input on how the outcome is achieved, because it is intended to be solution independent. However, some consumers want to select specific subsystems of the system. Once the engineering characteristics of the system are known, and performance values are set, a representation of the system needs to be created to move forward in the design process.

Product Architecture looks at representing the system in an abstract form, defined by Ulrich as “the scheme by which the function of the product is allocated to physical components” [28]. The first step is to determine the arrangement of functional elements, which is essentially a high level functional model.

Methods of functional modeling and mapping have been explored by a number of individuals; Hirtz et al. provides an overview and synthesis in [11]. A high level functional model is largely form independent, however, as the functional model is further developed, it places more constraints on what physical solutions are realizable. Eventually, the functions will need to be mapped to the components that perform them; one method of doing this is to use the Function-Component Matrix [29].

These early design process tools are general enough that they can be used to assist within the different design methodologies that exist to facilitate meeting the various segments. The following sections discuss three of these main design methodologies: product families, reconfigurable/changeable systems, and mass customization.

2.3 Product Families

Product families offer companies a means of providing increased product variety while leveraging economies of scale. A product family is a group of products with a common core, called a product platform, of which different family members satisfy the requirements of different market segments. While several definitions exist in the literature for product platforms [30-32], the general consensus is that a product platform is a collection of common parts, assemblies, or processes that are shared amongst a group of products (i.e. shared by the product family).

Significant research has been done regarding how to realize product families in a design firm, both in terms of the corporate approach, and the system level approach. Organizations can take a top-down or bottom-up approach to product family design [33]. Further, for the product platform a module based approach and a scale based approach are available [34]. Research has looked at how to identify platform elements within existing products [35]. In this bottom-up method, unique functionality is preserved, but this assumes the current functionality properly serves the segments. Further, it assumes that a product family is the best approach to satisfy the differing needs of the market segments.

A top-down method of developing hierarchal product families which offer better performance while covering a given market area is presented in [36]. Hierarchal platforms specify multiple levels of commonality, essentially forming a tree of discrete options. The idea behind this is not to limit performance to increase commonality. [37] went on to extend this work by looking at how non-uniform demand affected this.

Commonality indices have been developed to assist with assessing how much the product family shares [12-14]. This helps companies assess how well they are leveraging the platform. However, many of these approaches use little marketing information to determine what should or should not be common. Regardless of how they are developed, product families strive to better match consumer preferences by offering variety of product options. Another approach to meet consumer preferences is to allow the system to be configured to (or by) the user, as described in the next section.

2.4 Reconfigurable/Changeable Systems

In response to the challenges of dynamic marketplaces, rapid technological evolutions, and a variety of operating environments, Shulz and Fricke identify changeable systems – a system that can be easily modified at any point in its lifecycle – as a viable solution to handle these new challenges [38]. A changeable system is one method that can be used to allow Adaptive Customization, defined by Pine as customization that is carried out by the consumer upon receipt of the product [39]. This requires either a configurable (changeable) or reconfigurable system to allow the system to achieve different states (presumably to alter the performance in some way). A configurable system is a system which can be altered after it has been fielded; a reconfigurable system is a system in which these configurations can be changed repeatedly and reversibly [40]. Thus, reconfigurable systems are a subset of configurable systems.

Research in reconfigurable systems has looked at a broad range of subjects such as costing [40], design variable selection for reconfigurability [42-44], stability during reconfiguration [45], and methods for achieving reconfigurability [46]. This section looked at approaches to better meet the preferences of consumers and create system designs that are capable of dealing with change, regardless of its origin. However, to economically build systems that can take into account individual customer preferences, design firms must be able to identify where these abilities are truly needed to make the system successful. One possible use of reconfigurability is to account for occasion-based needs. Another possible use for reconfigurability or configurability is in realizing a mass customization methodology, discussed in the following section.

2.5 Mass Customization

Product families were viewed as a method for achieving mass customization. However, certain consumers want more control than what is offered by picking the product family.
member which is closest to what they truly desire. Research into how product families can be leveraged in mass customization is ongoing. Tseng identifies product families as a viable option in his Design for Mass Customization framework [47]. Specifically, Tseng looks at setting up Product Family Architectures that facilitates family based design which can serve as a basis for customizable products [48]. Du et al. expand this idea and look at how a platform based approach could be used in a customization process [49]. They suggest that adding, swapping, or scaling modules are three different ways of generating product variants capable of supporting mass customization.

When developing a system for mass customization, flexibility is required because individual consumers are specifying design requirements that the system must achieve after the general product architecture has been established; detailed dimensions for user interfaces may also be specified. At this point, the system has essentially been “fielded” as the engineers are no longer in the design loop, which means the system must be able to adapt to meet the specified requirements. This has specific implications for the product architecture that must be designed into the system. Most of the design methodologies consider what factors impact the system; the next section considers what factors impact the design methodology itself.

3.0 INFLUENCES ON DESIGN METHODOLOGY

The following sections look at factors which can influence which design methodology should be used to satisfy consumer variation in the market. The main driver is the consumer, or more specifically the group of consumers. However, there are also considerations related to the system and design firm that must be considered.

3.1 Consumers

The targeted consumers play a major role in determining what methodology is appropriate. For this reason, detailed demographic and psychographic profiles are needed. Current product usage and familiarity should be determined as well. This information can be used to determine consumer needs regarding point of sale, desire to customize, knowledge of the system, and other preferences that are not necessarily specific to the system being designed, but are related to more general social, emotional, and functional needs. However, these needs can impact which methodology is most appropriate for the design of the system.

3.2 System

The system(s) being sold influences to an extent what approach should be taken by the design firm. For example, some products lend themselves well to being part of a product family or towards mass customization. Further, of those products that are part of the family, some products will be better suited to modularity, scaling, or a combination of the two. Computers, for example, have developed with a high degree of subsystem modularity, leading this to be a means of achieving a family of products, or even allowing modular customization.

3.3 Design Firm

There are some characteristics of the organization which impact what approach should be taken as well. For example, an international organization will have to consider more factors in designing the product(s). Not only are there likely to be different sets of needs, but there will also be different system constraints. For example, the standard household voltage in Europe is 220 V while in the United States it is 110 V. A constraint like this alone might be enough to require two variants. The size, resources, etc. will also contribute to what resources the firm has to put towards development. However, this work focuses mainly on determining what approach should be best, not whether or not the design firm can implement the suggestion. The next section examines how consumer, system, and design firm information can be captured and analyzed, then used systematically to evaluate design options.

4.0 DETERMINE DESIGN METHODOLOGY

This section introduces a meta-design method in which the three factors discussed in the previous section are evaluated. This includes taking marketing information and using early design process tools to determine what design methodology should be implemented for satisfying consumer variation. The meta-design method is outlined in Figure 1. It starts with segmentation of the potential users and moves on towards determining a solution concept which is then evaluated by the marketing and engineering departments. The steps of the methodology are contained within design process stages which are similar to those found in most design processes, such as Pahl and Beitz’s Systematic Design [3], for perspective. These steps do not replace current design processes, but rather guide the existing process through the generation and analysis of information.

4.1 Clarification of Task

In this stage of the design process information is gathered and analyzed regarding what the requirements and constraints are for the system(s). It involves both the marketing and engineering departments to complete tasks such as segmenting the market, mapping consumer needs to system requirements, and integration of the two.

4.1.1 Segment the Market

The first step in the meta-design method primarily involves the marketing department; this step focuses largely on how consumers will impact the design methodology. The meta-design method begins by assuming that market research has been conducted to gather consumer information regarding needs, current usage, demographics, and psychographic information. The gathering of this information is costly, but it will also be used later to promote and sell the final product(s).
In segmenting the market, the prospective users are divided into various categories according to their needs. Consumer needs include: the desired functionality, along with the corresponding performance ranges and features (i.e. functional modifiers or specific subsystem solutions); geometrical constraints, generated by consumer morphology and preferences; and aesthetic needs, such as material preference, color, and finish. Demographic and psychographic information should be coupled to the various members of each segment to provide additional information for the segments.

To segment the consumers, any number of methods can be used. The key is to use segmentation methods that do not assume how the customer needs should be clustered. Further, the segments should show the user need variation within segments and the strength of fit of the users in the segments.

### 4.1.2 Convert Consumer Needs to System Parameters

Consumer needs are typically a mix of function and form requirements; these needs must be converted to system parameters. This process consists of two steps, mapping consumer attributes to engineering characteristics, and then associating these characteristics with system function and form. This information will be used when analyzing the market segments from the engineering domain.

For each segment, engineers must map consumer needs (attributes) to engineering characteristics; the first HoQ can facilitate this process. System requirements are then estimated for each engineering characteristic. These are typically used later in the design process to generate technical requirements for subsystems. With performance requirements estimated, the function structure for each segment can be created.

Functional consumer needs are typically high level. Considering the cell phone need “send email,” there are a number of subfunctions that are involved with this. These include the following: receive user input of text, display user input received, and connect to network; the last subfunction itself has multiple subfunctions. This decomposition needs to be done for each functional consumer need. Once the subfunction blocks have been developed, they are assembled into a system level functional diagram. Each market segment will have its own (possibly unique) functional diagram. Once the engineering functions of the device are known, the subsystems which will perform them can be considered. The subsystems are influenced by performance requirements, requested features, desired geometry, and safety regulations.

Desired features for the different segments need to be identified because they may impose specific subsystem solutions or identify additional required components. Safety regulations can constrain how subfunctions are completed, and may even impose additional subsystems. The safety regulations identified in the segmentation analysis need to be associated with the functions they affect, and how this impacts geometry, allowed materials, etc.

Each system has a set of geometry requirements attached to it. These include overall product envelop requirements (e.g. “fit in pocket”), as well as specific requirements that target more specific aspects of the system (e.g. “comfortable to hold”). These geometry requirements provide constraints for the subsystems. With more detailed information, engineers can begin to evaluate the variation across segments.

### 4.1.3 Analyze Market Segments

Once the consumer need information has been segmented, it can be analyzed to determine what the differences are between segments and within segments. While ideally segments will be heterogeneous, in practice segments are not. Even if segments are functionally similar, differences in form (aesthetics and geometry) will likely exist. The variation across consumers has a significant impact on the design methodology that should be used to fulfill the consumer needs. This step serves to interpret and organize the market and system information in such a manner that it is easy for engineers to process. Figure 2 shows a high level comparison of consumer need requirements across segments. The type and characteristics of these needs are evaluated in detail to determine implications for the design methodology.
Figure 3 shows a more detailed comparison of the needs common to all three segments (from Figure 2). It can be seen that for Need 3, there are three unique requirement ranges; this may necessitate three unique subsystems (potentially modules), a robust subsystem, or a (re)configurable subsystem. The decision of which to use will be evaluated in the next step. More importantly, how consistent the needs within each segment are should be noted.

Consumer needs related to geometry should be compared among the different segments and differences identified. Consumer needs related to product geometry can be enough to require major system changes (e.g. miniaturization), which can in turn impact what feasible design methodologies exist. Preferences regarding the product’s aesthetics should also be noted, particularly those coupled to product geometry. Ideally the cosmetic preferences within a segment will be similar from an engineering standpoint.

Once the commonality of the segments is identified, outside factors need to be noted as well, indicating specific requirements that must be met, which may not be indicated by the user. These requirements come from the design firm and the system. An example of design firm impact is imposed international safety regulations. While users from multiple countries may have the same needs, the safety regulations for the various countries will likely differ, not only in allowable limits but also in scope. Regulations on specific types of systems also exist (e.g. medical devices), and should be noted. Once all the segment information has been analyzed and organized, engineers can begin to examine possible system concepts and design process methodologies to use to satisfy consumer variation. This is discussed in the following section.

4.2 Conceptual Design

In the previous step, commonality among consumer needs was assessed. The section looks at how the quantitative and qualitative information can be used to develop a candidate design methodology for the realization of a product or product line which will satisfy the variety of consumer needs. To achieve this, potential product architectures are explored, which necessitates that the information used to generate them be created.

4.2.1 Generate Subsystem and Architecture Concepts

As in most design processes, concepts must be developed to satisfy the various consumer needs for form and function. To facilitate exploring all possible design methodologies, concept generation methods may want to be tailored to investigate particular design methodologies (e.g., (re)configurable design). Once concepts for fulfilling the different user needs are generated, meta-design information can be generated to assist in determining what design methodology to use.

4.2.2 Generate Meta-design Information

The different design methodologies rely on different system, design firm, and consumer characteristics. Exploring these methodologies involves looking at the consumer needs and system information to try and create solutions that leverage the system’s natural disposition. This involves evaluating the potential commonality, modularity, and reconfigurability options.

Identify Potential Commonality

This first place to start looking for system commonality is where there is existing functional commonality. Functional commonality can often lead to common components if the required performance ranges are similar. Across family members, the technical requirements for potential subsystem solutions should be compared. These technical requirements can be generated using the Subsystem Design Matrix, a HoQ from [5]. If there is large variation between the technical requirements for the different segments or within segments, multiple versions of the subsystem will be required (to form a static product family). Within segments it is desired that the performance requirements are fairly consistent. If significant performance ranges within a segment exist there are a number of options that can be taken.

Common functions are the most logical place to find commonality, however, simply because a consumer need is not common does not mean that it will require unique components. Looking at the function structure for the different segments, common components can be identified that will fulfill the different subfunctions across the various segments. If no apparent areas of commonality exist, either a robust solution or system variants will need to be developed. One way of generating variants is to use modularity.
Identify Potential Modularity

There are two aspects of modularity that need to be considered. The first step is to look at the functional model. A set of heuristics has been developed for identifying modules by examining a functional model [50]. Common modules between segments should be noted, as well as where modules interact with each other and the rest of the product architecture. The second aspect of modularity to be considered is the natural modularity of certain components and subsystems. Some components are naturally modular due to industry standards, function, etc. Where modularity does not exist, (re)configurability may exist.

Identify Potential (Re)configurability

(Re)configurability is a potential option for creating variety. Areas where there are performance tradeoffs are potential areas to look for (re)configurability options. For example, with gear trains than can be configured to be high torque, low RPM or low torque, high RPM using the same set of gears. A reconfigurable gear train (i.e. a transmission) can be used where these performance tradeoffs need to be repeatable and reversible.

Anthropomorphic constraints are also areas where (re)configurability can be used to overcome differences in consumer needs. Other geometric consumer needs can be achieved using (re)configurability as well. One benefit of (re)configurability is it can be used when the exact consumer requirements are not known. Free standing shelving units typically employ (re)configurability to allow users to specify shelf height. (Re)configurability has the benefit of offering a continuum to the consumer, while modularity is typically discrete. Once commonality, modular sections of architecture, and potential areas of reconfigurability are identified, design methodologies can be evaluated.

4.2.3 Assess Meta-Design Information

Based on the meta-design data, certain design methodologies will be more promising than others. The most promising design methodology can be identified by evaluating the meta-design information.

Product Family

While product families have been proven to offer a benefit when properly implemented [30], they are not appropriate for all situations. However, if there is commonality among the consumer needs, and the segments themselves are largely homogenous, a static product family should perform well, whether a top-down or bottom-up approach is being taken. If segments are not homogenous, there are three options.

The first option is to do nothing; select a robust solution and wait to see the results from the product review. For functions that are not critical to users, this may be the best option. This is where market research is critical; if the performance sacrificed is part of a noncompensatory need, it could endanger the success of the family member. The selection of a robust option does not imply a performance compromise is required. A component that meets the highest criteria could be used, but this will likely increase the cost.

The second option is to increase the number of product variants by changing modules. The difference in consumer needs may be easily accommodated by the addition or changing of modules. Modules can also be combined to perform a type of scaling, which is a subset of the third more general option.

The third option is to select an option that can be scaled to accommodate the different performance ranges required. An example of this was the scalable universal motor [30]. The use of a scalable subsystem increases the required amount of flexibility for that family member, so the product constraints will have to be checked to make sure this is feasible. If platforming does not appear to be a viable option, a (re)configurable system can be investigated.

(Re)configurable System

A (re)configurable solution can be used to address each segment, or it may be possible for one to address all the segments depending on the variation among segments. This design methodology has distinct advantages for satisfying performance requirements that are tied to anthropological constraints, as the user can make the final selection. However, this requires a certain amount of flexibility to allow the configuration to take place.

Reconfigurability also offers the possibility to accommodate for changing user preferences. This makes it a candidate for fulfilling consumer needs that can vary based on the occasion or usage. The design of reconfigurable systems can be aided with design tools, but using reconfigurability increases design complexity. If the system is not inclined to reconfigurability, unique products may have to be built to address the various segments.

Unique Products

If there is no common core of components, areas to use (re)configurability are scarce, and preferences are relatively homogenous among segments, individual products to suit each segment may be the best option. Unique products might also be the best option if there are large variations in the geometric envelope requirements for the different segments, which may require miniaturization that does not lend itself to scaling. On the other end of the spectrum, if there is a large degree of variation across segments, a mass customization approach may be needed.

Mass Customization

Mass customization may be needed to satisfy consumers if within segments there is a large variation of consumer needs; this is even more important when noncompensatory needs cannot be clustered. A platform or (re)configurable system may be the basis for this approach, but direct user input may be required to create the system. A mass
customization approach requires even more flexibility and careful planning of the architecture than the other approaches.

**Mixed Design Methodology**

A mixed design methodology may be the best method for satisfying all consumer variation. An example of this is a family of mountain bikes. There is a high level of functional commonality, with varying performance ranges. These performance ranges do not lend themselves well to (re)configurability, so modules are used. To better accommodate the anthropomorphic requirements of the rider, reconfigurability is used at these interfaces. Once the design methodologies have been evaluated and system architectures are explored, on design methodology needs to be selected to take through development.

### 4.2.4 Select and Test an Option

To select an approach many factors must be taken into account. Certain segments will be more promising for a variety of reasons. Marketing information can identify niche segments, as well as popular segments (where there will be a significant number of users and competition). The design methodology pursued may be the one that is likely to best deliver a product or product line that fits the market segments with the most promising predicted return. This selection process is largely dependent on the goals of the design firm. Apple offers only a few varieties to consumers, while Dell offers a wide variety of customization options; Apple targets consumers looking for a sleek solution to general problems, while Dell allows customers to optimize a machine to their performance requirements. These two different approaches have both been fairly successful.

Upon picking a design methodology, the design firm should validate that the design solution which that methodology produces has good potential to succeed. This can be done by using focus groups to evaluate the performance ranges which the various products can achieve. If a mass customization method is selected, it should be validated that the users in that segment feel comfortable using this approach. The following section presents a case study demonstrating how the approach can be applied to the design of line of computers.

### 5.0 CASE STUDY

The following case study uses data from a study on Latent Segmentation Models (found in [24]) as a basis for demonstrating the meta-design method. The segmentation data contains the original values, but the system requirements were disguised as the design of a computer. While this data is from 1998, it is demonstrative of the process that can be used, and highlights how a lack of segment information can significantly impair the ability to make sound design process decisions further along in the design process.

### 5.1 Clarification of Task

#### 5.1.1 Segment the Market

The market information which was used in creating the segments was generated using a simulated customization process. Potential customers were shown a menu of options from which they picked. This process was completed with several hundred potential users. The menu options consisted of mostly performance levels. However, asking consumers about technical performance requirements requires they have a more intimate understanding of how the system works; this is why segmenting on needs is recommended. For example, the case option points to questions on geometric needs, while the processor speed relates to performance needs. The results of the segmentation are found in Table 2.

From this we can see that Segment 1 is the largest segment, accounting for 45 percent of the total individuals surveyed. This segment was identified as consumers wanting basic features. The second segment, which was considerably smaller, was identified as the power user segment. The last two segments look for midrange performance, with the largest difference being that Segment 3 is more likely to want different software.

The percentages listed for each system requirement indicate what percentage of that segment wanted that performance level. Performance levels for a given segment which did not represent at least five percent of the total surveyed population are highlighted with a dark background.

#### TABLE 2: SEGMENTATION DATA

<table>
<thead>
<tr>
<th>System Requirements</th>
<th>Segment 1</th>
<th>Segment 2</th>
<th>Segment 3</th>
<th>Segment 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip Speed (MHz)</td>
<td>CS1 133</td>
<td>CS2 166</td>
<td>CS3 233</td>
<td>CS4 266</td>
</tr>
<tr>
<td>RAM (MB)</td>
<td>R1 32</td>
<td>R2 64</td>
<td>R1 128</td>
<td>R1 4</td>
</tr>
<tr>
<td>Drive Capacity</td>
<td>D1 1</td>
<td>D2 2</td>
<td>D3 3</td>
<td>D4 4</td>
</tr>
<tr>
<td>Monitor Size</td>
<td>M1 15</td>
<td>M2 17</td>
<td>M3 17</td>
<td>M4 17</td>
</tr>
<tr>
<td>Video Card</td>
<td>V1 1</td>
<td>V2 2</td>
<td>V3 3</td>
<td>V4 4</td>
</tr>
<tr>
<td>Software</td>
<td>S1 85%</td>
<td>S2 95%</td>
<td>S3 95%</td>
<td>S4 41%</td>
</tr>
<tr>
<td>Case</td>
<td>T1 21%</td>
<td>T2 21%</td>
<td>T3 21%</td>
<td>T4 21%</td>
</tr>
</tbody>
</table>

#### 5.1.2 Convert Consumer Needs to System Parameters

A significant portion of the consumer needs gathered were performance requirements, however there is one criterion, the case, that needs to be converted to engineering attributes and have technical requirements associated with it. The case’s primary function is to house components, and potentially raise
the monitor off the desk. This correlates to a geometric envelope. Without more detailed consumer data, engineers would be forced to speculate that consumers who want a desktop version would like a small case that can fit easily on a desk, and raises the monitor several inches. Those who want a tower version would like more space to allow them to install more components. An additional factor that may differentiate the two is how well they allow the users to customize post-purchase, which could influence how much flexibility the system needs.

A functional model for the computer is shown in Figure 4. This is used in evaluating potential areas of modularity. Because all the functional needs for the four segments are the same, only one functional model needs to be developed. If the needs were recaptured currently, there could be significant differences in what consumers want to do with their computers, which may lead to different functional models.

![FIGURE 4: FUNCTIONAL MODEL FOR COMPUTER](image)

5.1.3 Analyze Market Segments

Because of the nature of how the data was collected, all segments have the same basic functions, but with different performance requirements. Examining the data, it can be seen that there are certain combinations that do not need to be offered, and several others that have a very small market share that could potentially be eliminated if they are not projected to be profitable. Unfortunately, the specific user data is not available.

A more detailed set of the consumer needs would allow the designers to identify what variety is truly needed, which could significantly alter the design methodology chosen. Currently there is significant variety within the segments. As a coarse filter, segment variations that represent less than five percent of the total have been highlighted.

A constraining consumer need that should be noted is the desktop version, as this will impact the available geometric envelope. One interesting observation is that there is a small demand for monitors larger than 17 inches. All of the segments combined make up just over 11 percent of the market. This option may not be offered, however, if it can be accommodated easily, the design firm may want to include it.

Examining the comparison of needs (Figure 5), it can be seen that there is a fair amount of variation in the first segment; 16 of the potential 22 performance levels are desired. Segment 1 also requires five performance levels from three different characteristics that are not used by any other segment. If the user data were available, the investigation of breaking this into smaller segments should be completed. It may be that three variants could adequately serve this segment. However, without this knowledge it is assumed that there is no further segmentation that can be done, and these differences in preferences must be addressed. Segment 3 and Segment 4 also have a large amount of variation in desired performance requirements. However, Segment 2 can be completed with one product variant if the less popular performance levels are ignored.

![FIGURE 5: COMPUTER CONSUMER NEED COMPARISON](image)

5.2 Conceptual Design

5.2.1 Generate Subsystem and Architecture Concepts

In this section product line options are developed based on the characteristics of the system, and the information generated in the previous two steps. There are three key areas that need to be addressed: information processing, storage, and display.

For storage requirements, hard drives were available. However, there are two options for adjusting storage capacity. First, change the number of disks in a hard drive, or second change the number of hard drives. For processing requirements, you can change the amount of RAM, processor speed, and number of processors. For display requirements, you can adjust the monitor size and video card resolution. There may also be potential to use multiple video cards and monitors.
5.2.2 Generate Meta-design Information

Identify Potential Commonality

While there is variation between segments and within them, there is still a relatively large amount of commonality. The consumer needs are identical from a functional need standpoint, but have different performance requirements. However, the nature of the performance requirements is that they are typically shared by the various segments, at least to an extent. This offers a distinct possibility that the components which fulfill the performance can be shared by the different segments. A potential challenge to do this is the different geometric requirements.

Identify Potential Modularity

Looking at the function structure in Figure 4, it can be seen that the monitor can be a module, which connects to the components which process information which are housed in the case. The monitor serves primarily one function, and has only one connection to other functions. The store information and receive user input components could also be modules, however there does not appear to be a need for this based on the consumer needs.

Computer components are naturally modular, and this can be leveraged to fulfill different segment requirements, and performance differences within segments. This offers the possibility that the system can benefit from modularity even if the overall function structure does not lend itself to larger modules.

Identify Potential (Re)configurability

The nature of the variation in performance and component solutions does not lend itself well towards (re)configurability. One potential area that (re)configurability could be leveraged is in the getting the case to conform to the different geometric requirements of consumers. Also, with the modular nature of the components, lower performance components can be configured in parallel or series to create a solution that is capable of fulfilling higher performance requirements.

5.2.3 Assess Meta-Design Information

Based on the large variation in performance requirements between and across segments, a mass customization approach is determined to be a potentially effective design methodology. The systems natural modularity makes this a feasible approach.

Under the assumption that a desktop needs to be able to fit two hard drives, and a tower should fit four, either two cases need to be designed, or one (re)configurable. Because the design of a (re)configurable case is not that different, it will be explored as an option. Within these geometric constraints, the capability to modularly scale the system will be leveraged to accommodate the variation within and across segments.

The following solution in Table 3 is proposed to fulfill the variation required. These components allow a large range of segment variations to be achieved. Two processors, two sets of RAM, and up to four hard drives (in the tower) can be paired to achieve the numerous processing and storage variations that exist in the market. These components were chosen by trying to minimize the number of unique components while allowing the necessary variation to be achieved. In a more complex problem, this is not a trivial task, and investigating ways to automate this process is an area of future work.

<table>
<thead>
<tr>
<th>System Solutions</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip Speed (MHz)</td>
<td>133</td>
<td>166</td>
<td>233</td>
</tr>
<tr>
<td>RAM (MB)</td>
<td>32</td>
<td>64</td>
<td>NA</td>
</tr>
<tr>
<td>Drive Capacity (GB)</td>
<td>1</td>
<td>3</td>
<td>NA</td>
</tr>
<tr>
<td>Monitor Size (In)</td>
<td>15</td>
<td>17</td>
<td>NA</td>
</tr>
<tr>
<td>Video Card</td>
<td>Basic</td>
<td>High Resolution</td>
<td>Extra High Resolution</td>
</tr>
<tr>
<td>Software</td>
<td>Microsoft Office</td>
<td>Lotus SmartSuite</td>
<td>NA</td>
</tr>
<tr>
<td>Case</td>
<td>Tower</td>
<td>Desktop</td>
<td>NA</td>
</tr>
</tbody>
</table>

TABLE 3: PROPOSED COMPONENT LIST

While the monitor could be integrated with the desktop case (as the iMac in Figure 6 did), this would increase the number of components (each monitor size would require a unique case). Using a separate monitor module is thus chosen. Because of this, the design firm should investigate offering a 19 inch monitor as well; this would allow them to identically satisfy an additional ten percent of the market.

Software can be loaded according to order, or shipped with the machine for install. Basic users may be intimidated by this process, while the power users would likely be ok with the process. A third option is to install both software packages and a script that, given a product code, activates one of the software packages and deletes the other. These decisions can be made on a per segment basis.

FIGURE 6: INTEGRAL MONITOR AND DESKTOP CASE

5.2.4 Select and Test an Option

Under the assumption that the variation is needed, the mass customization approach that leverages a platform of common components appears to be a viable approach for satisfying the consumer variation; this is made possible by the modularity of components, and the ability to easily scale performance by pairing modules. How consumer needs are acquired to establish a final configuration needs to be determined, and this process should be tested as well. While the platform may allow customization on the different levels, consumer preferences on how they purchase the product can be just as important. If online customization and then shipping is the proposed plan, this must be tested on consumers as well.
5.3 Case Study Conclusions
The case study demonstrated that consumer, design firm, and system characteristics all influence what design methodology should be implemented to develop a product or product line, when satisfying a set of varying consumer needs. The natural modularity of computer components allows a mass customization approach based on modular product platforms to be used. While a (re)configurable solution could be developed, it would require a significant amount of new design work. This case study demonstrates that there are possible correlations between the three factors and the preferred design methodology which can be identified. Determining these design factors and empirically validating them is an area of future work. Further, while a relatively simple design problem, there is still a fair amount of information to manage and interpret; with increasing complexity of the system, the management of this information would be increasingly difficult to handle without meta-design support tools.

6.0 CONCLUSIONS AND FUTURE WORK
This research lays the foundation for the development of a more rigorous approach to design methodology selection by developing a meta-design method analogous to similar methods used in other scientific fields. While these design methodologies are fairly mature, one of the main assumptions in many of them is that the correct paradigm can be selected for a particular problem. This problem is complicated by the concept of mass customization, namely, when is appropriate to use it.

Suggestions and insights are made as to how information about the consumers, design firm, and system can be used in identifying which paradigm is appropriate, and when mass customization should be utilized. Current design tools are identified to assist designers with the generation and management of information. Once a design methodology is identified, design tools specific to that methodology can be utilized in the design of the product(s). As this is an initial effort in this area, future work is identified.

Future work will look at how this method can be extended to handle a wider range of consumer needs, such as the design of a line set of power tools, where there are larger changes in product functionality. Empirical studies will be used to further correlate market and system characteristics to what design methodology leads to success. Additionally, the development of metrics which assist with quantifying the segment variation will be investigated and correlated to the empirical study.

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