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UNIVERSAL PRODUCT PLATFORM AND FAMILY DESIGN FOR UNCERTAIN MARKET

Seung Ki Moon and Daniel A. McAdams
Texas A&M University

ABSTRACT

Designing new products for everyone requires numerous functions for many individuals and groups often differentiated by capabilities and limitations. In this paper, we extend concepts from product family and platform design and mass customization to create a method for universal product family design. The objective of this paper is to develop a universal design method to generate economical feasible design concept and evaluate design feasibility with respect to disabilities within a product family in uncertain market environments. In this research, we will consider a platform level problem as a module selection problem that is to determine design parameters in variant modules for unique or common modules by minimizing the production cost and maximizing accessibility in a universal product family. In particular, a Bayesian game is employed to model uncertainty situations regarding market environments. The proposed method is used to decide strategic equilibrium solutions for selecting modules in the universal product family being designed. To demonstrate implementation of the proposed method, we use a case study involving a family of kitchen products.

Keywords: Bayesian Game, Product Family and Platform Design, Universal Design

1 INTRODUCTION

Universal design is a recently suggested term for designing for persons with a disability [1]. Persons with limitations due to age and disabilities are not a static population with static abilities. Disability is a continuum. We will all likely be disabled at some point, be it temporarily through injury or permanently through injury or the effects of age. The number of people with a disability is between 40 and 50 million [2]. This number represents approximately 1 in every 7 Americans. Based on current demographic trends, particularly the aging population, the numbers of people with disabilities is expected to increase, perhaps significantly, for the foreseeable future.

Mass customization offers an avenue to provide persons with disabilities a wide array of products. Using mass customization methods, companies are increasing their efforts to reduce cost and lead-time for developing new products and services while satisfying individual customer needs. Mass customization depends on a company’s ability to provide customized products or services based on economical and flexible development and production systems [3]. By sharing and reusing assets such as components, processes, information, and knowledge across a family of products and services, companies can efficiently develop a set of differentiated offerings by improving flexibility and responsiveness of product and service development [4]. Product family design is a way to achieve cost-effective mass customization by allowing highly differentiated products to be developed from a common platform while targeting products to distinct market segments [5].

In this paper, we extend methods from mass customization and product family design to create specific methods for universal product family design. The objective of this research is to develop a universal design method to generate economically feasible product families in uncertain market environments. In this case, the universal product family includes products for persons with and without a disability. We use a module-based platform design by introducing universal modules, accessible modules, and typical modules for universal product family design. In this research, we will consider the design problem as a module selection problem that identifies a module or modules that establishes a viable product platform and associated product family. The primary trade off is minimizing production cost while maximizing accessibility of the universal product family. Alternate platforms and families are generated through negotiation with customers. We will use market-based decision-making approaches to consider dynamic design and market environments. Specifically, a

Bayesian game is employed to model uncertainty in market environments and determine strategic equilibrium solutions in the universal product family platform.

2 LITERATURE REVIEW AND BACKGROUND

2.1 Universal Design

A team of researchers organized through The Center for Universal Design at North Carolina State University has created seven principles of universal design [6]. The seven principles are: 1) equitable use, 2) flexibility in use, 3) simple and intuitive use, 4) perceptible information, 5) tolerance for error, 6) low physical effort, and 7) size and space for approach and use. For each principle, several guidelines have been created. For example, principle 6 has a guideline of “minimize repetitive actions.” These principles have been well received by designers in a range of disciplines. Though the seven principles of universal design provide high-level guidance, they provide more of an evaluation aid than a design or synthesis aid for product design. Vanderheiden [7] has developed a set of guidelines for the design of consumer products. Some of these guidelines are useful for evaluation but more challenging to use for product synthesis. Housed in the Center for Inclusive Design and Environmental Access at the University of Buffalo is an active group of researchers with focus on universal design [8, 9]. Though this group is focused on architectural design and comes from an architectural background, they have performed research on appliances and other applications that extend to product design. A team of researchers at the University of Cambridge has produced implementable results for universal design [10, 11]. The focus of this research group has been in modeling user groups, creating product assessment methods, and extending the needs of universal design to modern product design processes. The results of the Cambridge team are the most directly applicable to product design. Their effort has been primarily focused on the user and the design challenges of accommodating that user.

Universal design is an active research area. Nevertheless, fundamental work applicable to product design is still a sparsely populated space. Universal design is more of an objective than a systematic design approach. There is little in the way of a prescriptive approach to universal design in more detail than broad design objectives [12]. Additionally, though creating modular products that minimize modification to become universal is a recognized approach to universal design, specific knowledge and methods strategies to do it do not exist [11]. Methods that allow the design of universal products that offer value to the user and profitability to the producer have yet to be thoroughly developed.

2.2 Product family and platform design

A product family is a group of related products based on a product platform, facilitating mass customization by providing a variety of products for different market segments cost-effectively [13]. A successful product family depends on how well the trade-offs between the economic benefits and performance losses incurred from having a platform are managed. Simpson et al. [14] introduced a method to optimize a platform by minimizing performance loss and maximizing commonality based on a scale-based product family design approach. Gonzalez-Zugasti et al. [15] designed platform modules to minimize design risk and save costs related to develop a product family. Siddique and Rosen [16] described a method to design a platform from an existing group of products by comparing commonalities in assembly processes. Rai and Allada[17] used a two-step approach to determine a modular platform for a product family, which consists of an agent-based optimal technique and post-optimization analysis using the quality loss function. Johannesson and Claesson [18] proposed a configurable product platform design process and model using an operative product structure and a hierarchical function-mean tree to capture parameters describing design information such as rules, variants, requirements, and product configuration possibilities. Thevenot et al. [19] developed the design of commonality and diversity method (DCDM) to provide designers with recommendations for both the functional and component levels by the inherent tradeoff between commonality and diversity during product family and platform development. Moon et al. [20] introduced a market-based negotiation mechanism to support product family design by determining an appropriate platform level that represents the number of common modules using a dynamic multi-agent system in an electronic market environment. Zacharias and Yassine [21] proposed a mathematical model for developing and evaluating modular product families to provide maximum market coverage by integrating a conceptual design approach, a product development cost model, an economic model.

3 PLATFORM-BASED UNIVERSAL PRODUCT DESIGN

Figure 1 shows the process for developing a universal product family based on customer needs (CNs). Information required to identify CNs can be collected by surveying prospective customers and by conducting a marketing study that begins by establishing target markets and customers. In the initial phase, CNs are analyzed to understand customer intention and determine a strategy for developing a product family. For example, the number of products can be decided by customer groups and classified according to CNs. CNs are also used to identify appropriate functional requirements (FRs), which are then mapped to the CNs. Behaviors and functions for designing a product can be identified based on customers' needs and functional requirements using a functional model. In product design, FRs describe a product's behavior and features that are defined by technical information and data for its design. During conceptual design, products can be designed based on FRs, and their functional modules can also be determined. In particular, a family of universal products can be first configured by defining a product platform. A product platform consists of several common modules that can be shared across a family of product. After developing platform design strategies, through evaluation for products, a final platform is determined to provide universal product families according to design characteristics and market segments.

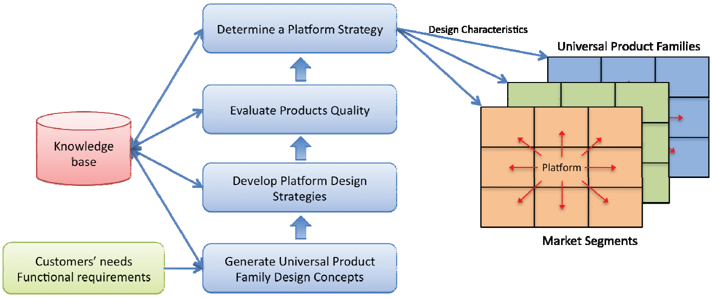

Figure 1. Process of Developing Universal Product Family Design

3.1 Universal Product Platform Framework

The universal product platform framework is built on representing the product space in terms of five different modules: common modules, varietal modules, universal modules, accessible modules, and typical modules. The notion of common and varietal modules is generally a well understood concept in product family design. Common modules are those shared across the product family regardless of the module's characterization with respect to typical and accessible products. In general, these common modules are suitable candidates for establishing the product platform. Varietal modules refer to the differing elements used to introduce variety into a range of products in the family. The common elements plus the varietal elements combined create a product family. The framework used to design a product family here is modular, but the notions of common and varietal need not be limited to a modular framework.

A module based product family strategy allows for the design and production of economically viable universal product families. Specifically, modules for universal design can be categorized into: 1) universal; 2) accessible; and 3) typical modules. Universal modules are those that are the same in function and form for both typical and disabled users. Accessible modules provide specific functionality or form solutions for persons with limitations due to age and disabilities. Typical modules contain functional and form solutions, or both, that are not suitable for user with a disability.

In the design of universal product families, different platform approaches need to be considered in an effort to create and leverage economies of scales. In evaluating approaches for a universal product family, the common modules evaluated as candidates for a product platform many come from universal or accessible modules, or some combination of both. The way in which the modules may interact to form different product families is illustrated in Figure 2.

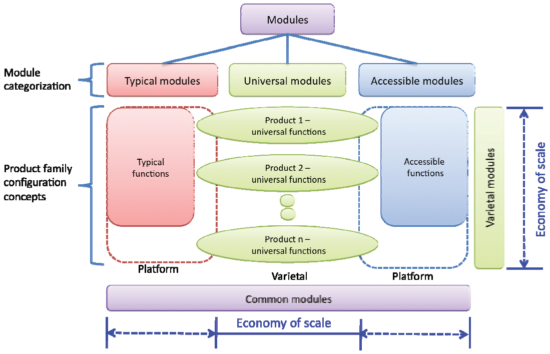

Figure 2. Module Categorization and Platform based Product Configuration Concepts

3.2 Platform Design Strategy and Cost Model

A well-defined platform reduces production costs by improving economies of scale and reducing the number of different components that are used [13]. Platform level is defined as the number of modules in the platform that may contain the common functions [20]. An appropriate platform level for a universal product family can be determined by minimizing the production costs associated with accessible modules and typical modules for commonality levels. As such, the appropriate platform level for the universal product family can be represented as a mathematical programming model in which there is a trade off between production cost and customer satisfaction, or more practically, customers willingness to pay for the product.

Based on generated product design concepts, we assume that product cost can be determined by combining components and assembly cost related to the design concepts through bill-of-materials (BOM). Suppose that a product family consists of I products, $PF = (P_1 P_2, ..., P_i, ..., P_I)$ and product i decomposes into three modules as universal modules, $\mathbf{x}^U_{i,j}$ $(j = 1,2,...,u_j)$, accessible modules, $\mathbf{x}^E_{i,k}$ $(k = 1,2,...,e_k)$, and typical modules, $\mathbf{x}^F_{i,d}$ $(d = 1,2,...,f_d)$. Each module can be represented by one or more components.

Let $C^M_{i,m}$ be component cost of $x^M_{i,m}$ (*M*= *U*, *E*, and *F*, *m*=*j*, *k*, *and d*) and $AC^M_{i,m}$ assembly cost of $x^M_{i,m}$. To develop platform design strategies, we consider the case where a typical product and the accessible product have the same functionality and essentially morphology of solution, but the parametric nature of the accessible product is different at some or all component levels. We will term these types of components design parameter (DP) components as the change from typical to accessible is a parametric design change to some different value or level, not a functional change.

For representing the component cost of different DP values, we assume that the parameter component cost has a non-decreasing linear cost function for DP values creating a more accessible product. We recognize that this is not always the case, but if it is not then the designer is not faced with a cost-accessibility trade off. Let $DPC^E_{i,k}$ be DP component cost of $x^E_{i,k}$ for a minimum DP value. Now, DP component cost can be formulated at the component level as follows:

$$C^E_{i,k} = (1 + a_{k,level_i}) DPC^E_{i,k} \tag{1}$$

where, $a_{k,level_i}$ is a coefficient that grows larger as the parametric configuration becomes more accessible $(0 \le a_{k,level_i})$ in product i. Hence, product i cost, PRC_i can be formulated at the component level as follows:

$$PRC_i = \sum_j (C^U_{i,j} + AC^U_{i,j}) x^U_{i,j} + \sum_k (C^E_{i,k} + AC^E_{i,k}) x^E_{i,k} + \sum_d (C^F_{i,d} + AC^F_{i,d}) x^F_{i,d} \tag{2}$$

where

$$x^U_{i,j} = \begin{cases} 1, \text{ if component } j \text{ is included Product } i \\ 0, \text{ otherwise} \end{cases},$$

$$x_{i,k}^{E} = \begin{cases} 1, & \text{if component } k \text{ is included Product } i \\ 0, & \text{otherwise} \end{cases}$$

, and

$$x_{i,d}^{F} = \begin{cases} 1, & \text{if component } d \text{ is included Product } i \\ 0, & \text{otherwise} \end{cases}$$

A designer determines a feasible set of strategies for the platform based on components' specifications and his/her design knowledge. The strategies for a platform are represented as alternative designs that can be constructed by combining components in common and variant modules based on DP values. Let S be a set of strategies and $c(s_y)$ the expected strategy cost for designer's strategy s_y (y=1,…,S) Then, the expected strategy cost can be calculated based on product cost and family design as follows:

$$c(s_y) = \eta \times \frac{\sum_{i \in I} PRC_i}{f \times r} \qquad (3)$$

where η is a factor for overhead cost and f is a strategy weight function associated with the benefit of family design as follows:

$$f = \begin{cases} 1, & \text{if product is unique} \\ I, & \text{otherwise} \end{cases} \qquad (4)$$

and r is a volume factor related to product sales quantity. For a given set of products, the value of $c(s_y)$ varies depending on DP values for accessible or typical modules. The expected strategy cost function will be used to determine a platform for a universal product family and can be developed by various cost functions based on products' characteristics and company's strategy in product family development or both. The next section introduces a product quality model for evaluating accessibility in a universal product.

3.3 A Product Quality Model for Universal Design

A usability testing and a participatory design model help designers evaluate design characteristics and functionalities for universal products in an early design process or a conceptual phase [22, 23]. To evaluate and measure accessibility of a product, we propose a product quality function that is positively related to design accessibility level (L) and user skill level (S) as follows:

$$Q = f(L,S) \qquad (5)$$

The design accessibility level represents a capability of supporting accessibilities by a product. The value of the accessibility level, $0 < L \leq 1$, can be determined based on the ICF [24] or the principles of universal design [6, 25]. For example, if a product is designed to support full accessibility, the value is 1. Otherwise, the value can be determined by design characteristics or parameters related to accessibilities. The accessibility level is problem-dependent, but an example can be found in the kitchen product case study. For the user skill level, we will categorize usability into five groups based on skill and capability in product utilization [24]: (1) No, (2) Mild, (3) Moderate, (4) Severe, and (5) Complete impairments.

The expected product quality, Q_i for product i can be estimated by an expected quality function: $f^i : L \times S \mapsto \Re$. Hence, the real number of $f^i(l,s)$ represents the quality of product i having accessibility level l for user skill s. For example, the expected product quality for product i can be determined as:

$$f^i(l,s) = l \times s \qquad (6)$$

where s is a skill level function as follows:

$$s = \begin{cases} 1 & \text{for No difficulty} \\ 0.75 & \text{for Mild difficulty} \\ 0.5 & \text{for Moderate difficulty} \\ 0.25 & \text{for Severe difficulty} \\ 0.05 & \text{for Complete difficulty} \end{cases}$$

(7)

The proposed product quality function will be applied to measure accessibility for determining product' values in terms of platform design strategies. In this research, we will consider a platform level problem as a component selection problem that is to determine design parameters in accessible modules, typical modules, or both by minimizing the production cost and maximizing accessibility in a universal product family. The next section discusses a Bayesian game model for determining a platform design strategy.

3.4 Bayesian Game for Decision-Making

A platform selection problem can be considered as a strategic game with incomplete information. The strategic game provides a useful technique for determining a strategy in uncertain environments [26, 27]. In this paper, we employ a Bayesian game to solve the platform selection problem in given universal product family design. Consider the following a scenario for a platform design problem in an uncertain market environment. There are two players: (1) a designer who has platform design strategies for a product family and (2) a customer who has prices they are willing to pay for a product. The designer provides a product with the cost *c*, and the customer pays the price *v* for the product. The product's cost and the product's price are dependent on the market share ratio of the products and customer's preference, respectively. The market share ratio and the customer's preference are assumed to be independently and uniformly distributed based on their market situations that represent the product sales. For instance, the values of the market share ratio can be determined by the proportion of sales volumes. The cost and the price are constrained to be non-negative. We assume if the market share ratio is greater than or equal to the customer's preference, then the product will be produced at a price equal to the average of the product's cost and the product's price; otherwise, the product will not be produced. Finally, we assume that the players are risk-neutral for their payoffs. Each player knows his or her own payoff function but may be uncertain about the other player's payoff functions.

In order to formulate the proposed scenario as a Bayesian game, we must first identify the action spaces, the type spaces, the beliefs, and the payoff functions [26]. In this paper, Player 1 is a designer who knows platform design strategies for a product. Player 2 is a customer who wants to buy a product below some maximum price.

Player 1's action is to select a strategy among design strategies that are all possible combinations for the platform design. The set of actions, $A_1 = \{a_{1,1}, a_{1,2}, ..., a_{1,n_1}\}$, for Player 1 are represented by the design strategies that can be developed by a designer for products. The set of types, $T_1 = \{t_{1,1}, t_{1,2}, ..., t_{1,m_1}\}$, are the values of the market share ratio for the products that are contained within the product family. For computational purposes the values are obtained from 0 to 1 where 1 reflects full saturation of the product in some population. Because the values of the market share ratio are independent, Player 1's belief is explained as the probability, b_1, that is uniformly distributed on $[0,1]$. Therefore, Player 1's belief is the probability of selecting a value of the market share ratio with a uniform distribution.

Player 2's action is to determine the price of the product. The set of actions for Player 2, $A_2 = \{a_{2,1}, a_{2,2}, ..., a_{2,n_2}\}$ constitutes market prices based on the product cost. In this paper, we define the market price as $(2 \times c(s_i))$, where $c(s_i)$ is the expected strategy cost as mentioned in Section 3.2 ($i \in n_1$). We assume that products' prices positively depend on their quality and customers' preference. The set of types of Player 2, $T_2 = \{t_{2,1}, t_{2,2}, ..., t_{2,m_2}\}$, are represented by customer's preferences. The customer will try to select an action that gives a higher pay off based on the customer's preference. For computational purpose, the values of the preferences can be obtained from 0 to 1 where 1 means a customer is willing to buy a product with 100%. Because the values of the customer's preference are independent, Player 2's belief is represented as the probability, b_2, that is uniformly distributed on $[0,1]$ and is the probability of selecting a value of the customer's preference with a uniform distribution.

The actions and types, A_1, A_2, T_1, and T_2, are finite sets that are defined by the number of n_1, n_2, m_1, and m_2, respectively. Therefore, Player 1 may be uncertain about the Player 2's payoff functions, since Player 1 may be uncertain about the types of Player 2, denoted by t_{-1}. In this game, the probability distribution $b_1(t_{-1} \mid t_1)$ is defined as Player 1's belief about Player 2's types, t_{-1}, given Player 1's knowledge based on type, t_1. According to the proposed scenario, Player 1 and Player 2 can have two possible payoff functions based on their selected types. The two players' payoff functions are given by:

$$u_1(a_1^*, a_2^*; t_1) = (c+v)/2 - c,\ if\ t_1 \geq t_2 \tag{8}$$

$$u_2(a_1^*, a_2^*; t_2) = (c+v)/2 - v,\ if\ t_1 \geq t_2 \tag{9}$$

$$u_1(a_1^*, a_2^*; t_1) = u_2(a_1^*, a_2^*; t_2) = 0,\ if\ t_1 < t_2 \tag{10}$$

where *c* is the expected cost based on a_1^* and is calculated by the expected strategy cost mentioned in Section 3.3, and *v* is the price of the product based on a_2^* and is calculated by (the market price × the product quality × t_2). Formally, this game is denoted by $G = \{A_1, A_2; T_1, T_2; b_1, b_2; u_1, u_2\}$.

In the scenario, Player 1 will try to seek to a platform that provides more profits from a product family in uncertain customers' preferences based on minimizing the expected strategy cost in various market share ratios. Player 2 wants to buy a product that provides high quality while minimizing product cost. In the proposed Bayesian game, a strategy for Player 1 can be represented by a function $a_1(t_1)$ specifying the market ratio that Player 1 would choose. In a Bayesian Nash equilibrium, Player 1's strategy $a_1(t_1)$ is a best response to Player 2's strategy $a_2(t_2)$, and vice versa. Based on Definition of Bayesian Nash Equilibrium [26], The pair of strategies $(a_1(t_1), a_2(t_2))$ is a Bayesian Nash Equilibrium, if for each t_z in $[0,1]$, (*z*=1,2), $a_z(t_z)$ solves:

$$\max_{a_z \in A_z} \sum_{t_{-z} \in T_{-z}} u_z(a_1^*(t_1), a_2^*(t_2); t) b_z(t_{-z} \mid t_z) \tag{11}$$

In this game, strategies for Player 1 represent the various platform design methods depending on the DP values of accessible or typical modules in a product family. Therefore, design parameters' values for platform design can be determined by selecting strategies in uncertain market environments.

4. CASE STUDY

To demonstrate implementation of the proposed Bayesian game, a kitchen product family consisting of a bottle opener, a serrated peeler, a Y peeler, a grater, a potato masher, and a jar opener is investigated. These items are shown in Figure 3. The Oxo Good Grips line of kitchen and hand-held products provide a good example of common and differing parametric solutions for cases where product functions remain the same. These products offer the opportunity to create a product family with the handle serving as a common module that constitutes the product platform and the end effectors as varietal modules.

The objective in this case study is to determine a platform design strategy represented by DP components for the kitchen product family subject to an incomplete information environment. This case study focuses on how to model a game and find Bayesian Nash Equilibrium for the platform design of the family of kitchen products using the proposed game at the conceptual stage of development.

Figure 3. OXO Cooking Products with the Same Grip (Source: http://www.oxo.com)

4.1 Platform Design Strategies and Expected Cost

Currently, these products have an accessible module related only to the grips at the platform level. Based on the information from product analysis, we can define components for designing accessible modules (i.e., grips) as shown in Table 1. The information includes length, width, thickness, and materials.

Table 1. Design Information for the grips

Grip	Length	Width	Thickness	Material
Y Peeler	9.2 mm	3.8 mm	1.8 mm	Santoprene + Plastic (inside)
Serrated Peeler	10.2 mm	3.6 mm	2.3 mm	Santoprene
Potato Masher	10.2 mm	3.6 mm	2.3 mm	Santoprene
Bottle Opener	9.9 mm	3.6 mm	2.5 mm	Santoprene + Plastic (inside)
Grater	9.9 mm	3.6 mm	2.5 mm	Santoprene + Plastic (inside)
Jar Opener	9.9 mm	3.6 mm	2.5 mm	Santoprene + Plastic (inside)

Since the grip module is an accessible module that consists of a component, we suppose that the module is involved in designing the platform. Therefore, appropriate DP values for the accessible module can be determined by a game to design the platform in a product family. The designer can select components to develop design strategies based on the DP values. Table 2 shows possible design strategies of the grip module for a platform based on the results of the product analysis. We generate the numerical data based on unit cost that is depended on components' design parameter values as mentioned in Section 3.2. We assume that the component cost of a minimum DP value is defined as 1 unit for length, width, and thickness, respectively. We use a normalization approach to determine the other component costs based on a minimum DP value. Table 2 shows the component cost of a DP module that can be calculated by Equation (1). Suppose that Table 2 illustrates costs related to components for generating platform design strategies in a market. The other components for designing the products can be determined from an auction based on market mechanisms to minimize total production cost [28]. Based on the grip design strategies, we developed platform design strategies by the combination of different grips for the products. Table 3 shows six platform design strategies for the six products. The s_{m1} can be considered as a current grip design strategy.

Table 2. Grip Design Strategies for DP Module Design

Module	Design Strategy	DP value	Cost
Grip	*D1*	9.2×3.8×1.8 mm	3.06 (=1+1.06+1) unit
	D2	10.2×3.6×2.3 mm	3.39 (=1.11+1+1.28) unit
	D3	9.9×3.6×2.5 mm	3.47 (=1.08+1+1.39) unit

Table 3. Platform Design Strategies for the Grip

Module	Platform Strategy	Products					
		Y Peeler	Serrated Peeler	Potato Masher	Bottle Opener	Grater	Jar Opener
Grip	S_{m1}	*D1*	*D2*	*D2*	*D3*	*D3*	*D3*
	S_{m2}	*D1*	*D1*	*D1*	*D1*	*D1*	*D1*
	S_{m3}	*D1*	*D2*	*D2*	*D2*	*D2*	*D2*
	S_{m4}	*D1*	*D3*	*D3*	*D3*	*D3*	*D3*
	S_{m5}	*D2*	*D2*	*D2*	*D2*	*D2*	*D2*
	S_{m6}	*D3*	*D3*	*D3*	*D3*	*D3*	*D3*

In this case study, we assume that the costs of universal components for all products are same. Therefore, the expected strategy cost focuses on accessible components for a platform. To determine the expected strategy cost, we use the expected cost functions, Equation (3). We assume that a factor of overhead is 2 units and an assembly cost for a product is 1 unit. Therefore, the expected strategy cost for s_{m2} is 1.353 units, if the value of a strategy weight and a volume penalty factor are 6 and 1, respectively. The value of a strategy weight can be determined by the proportion of the maximum numbers of products applying a DP component mentioned in Section 3.2. For the individual product design strategies (s_{m1}, s_{m3}, or s_{m4}), we used the average of the expected strategy costs for the products. To determine the expected qualities of products that are developed by the platform design strategies, we performed product analysis as shown in Table 4. Table 5 shows six expected strategy costs, the market prices, and the product prices, when the values of market share ratio (MSR) and customers' preference (CP) are both 1.

Table 4. The Expected Qualities for the Platform Design Strategies

Strategy	Product	Design accessible level*	User skill Level**	Quality	Average quality
S_{m1}	Y Peeler	1	0.75	0.75	0.8333
	Serrated Peeler	1	0.75	0.75	
	Potato Masher	1	1	1	
	Bottle Opener	1	1	1	
	Grater	1	0.75	0.75	
	Jar Opener	1	0.75	0.75	
S_{m2}	Y Peeler	1	0.75	0.75	0.5375
	Serrated Peeler	0.7	0.75	0.525	
	Potato Masher	0.7	1	0.7	
	Bottle Opener	0.5	1	0.5	
	Grater	0.5	0.75	0.375	
	Jar Opener	0.5	0.75	0.375	
S_{m3}	Y Peeler	1	0.75	0.75	0.7083
	Serrated Peeler	1	0.75	0.75	
	Potato Masher	1	1	1	
	Bottle Opener	0.7	1	0.7	
	Grater	0.7	0.75	0.525	
	Jar Opener	0.7	0.75	0.525	
S_{m4}	Y Peeler	1	0.75	0.75	0.7458
	Serrated Peeler	0.7	0.75	0.525	
	Potato Masher	0.7	1	0.7	
	Bottle Opener	1	1	1	
	Grater	1	0.75	0.75	
	Jar Opener	1	0.75	0.75	
S_{m5}	Y Peeler	0.5	0.75	0.375	0.6458
	Serrated Peeler	1	0.75	0.75	
	Potato Masher	1	1	1	
	Bottle Opener	0.7	1	0.7	
	Grater	0.7	0.75	0.525	
	Jar Opener	0.7	0.75	0.525	
S_{m6}	Y Peeler	0.5	0.75	0.375	0.6833
	Serrated Peeler	0.7	0.75	0.525	
	Potato Masher	0.7	1	0.7	
	Bottle Opener	1	1	1	
	Grater	1	0.75	0.75	
	Jar Opener	1	0.75	0.75	

* We assume that the design accessibility level of a grip is determined by the size of the grip. If the size is the same of the original one, the value of the level is 1. Otherwise, the value is 0.7 or 0.5 depending on the size.
** A safety is considered as the skill level.

Table 5. Expected strategy costs and product prices for the Grip module (MSL and CP =1)

Platform Strategy	Expected strategy cost	Market price	Product price
S_{m1}	3.078	6.156	5.1298
S_{m2}	1.353	2.706	1.4545
S_{m3}	2.817	5.634	3.9906
S_{m4}	2.843	2.843	4.2406
S_{m5}	1.463	2.926	1.8896
S_{m6}	1.49	2.98	2.0362

4.2 Bayesian game and results analysis

The game between a designer and a customer for platform design of this family is defined as the proposed Bayesian game described in Section 3.4. Table 6 summarizes the Bayesian game for determining a platform strategy for an accessible module with two players. In this case study, the Bayesian game focuses on determining a DP component for a platform based on designer's action.

Table 6. A Bayesian game for determining a design strategy

Bayesian game	Player 1	Player 2
Player	Designer	Customer
Action	Select a design strategy	Select a market price
Type	Market share ratio	Customer's preference
Belief	Uniform probability [0, 1]	Uniform probability [0, 1]
Payoff function	Profit *(v+c)/2- c*	Profit *(c+v)/2- v*

To determine the best response of Designer and Customer, we performed a sensitivity analysis for various market share ratios based on Customer's strategies as mentioned in Section 3.4. Figure 4 shows the Designer's payoffs for platform strategies based on different market price strategies, when the Customer's preference is 0.6. The Designer's payoffs were calculated by Equations (8) through (10). Then, we determined a maximum payoff as Bayesian Nash Equilibrium within the given Customer's preference.

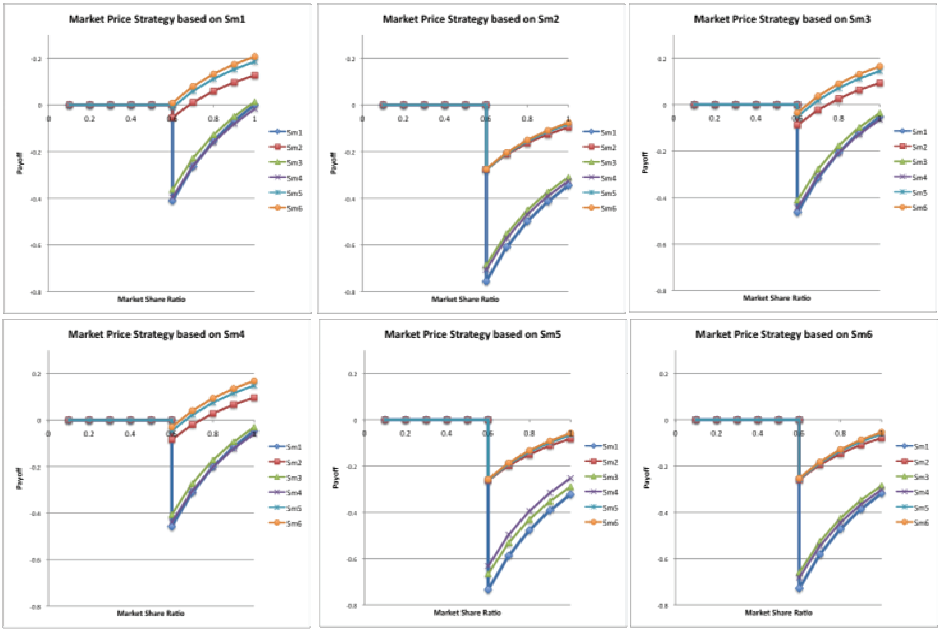

Figure 4. The Payoffs of a Designer for the Grip Module when Customer's Preference is 0.6

In these cases, s_{m6} is a dominated strategy based on the Designer's payoff in six different market price strategies. Therefore, a grip module with length 9.9 mm, width 3.6 mm, and thickness 2.5 mm can be designed as a new platform. The case study also demonstrated that the platform-based design strategies (s_{m2}, s_{m5}, and s_{m6}) provided more payoffs than the individual product design strategies. The results from a sensitivity analysis provide a designer with information for determining a platform strategy in an uncertain market environment. In conclusion, if the customer's preference is predicted as 0.6, a new platform for the six products can be identified as a grip with length 9.9 mm, width 3.6

mm, and thickness 2.5 mm. Comparing this to the current grips for the six products, we can take the benefit of family design based on common functional features in universal design.
Through the case study, the proposed Bayesian game was demonstrated to determine the DP value of an accessible module to select appropriate modules for the platform. Therefore, the Bayesian game can facilitate universal product family design in various dynamic market environments.

5. CLOSING REMARKS AND FUTURE WORK

In this paper, we have introduced a method for platform-based universal product family design through a game theoretic approach in an uncertain market environment. Module-based design was introduced to allow a range of trade-off in determining the specific platform configuration. To evaluate and measure accessibility of a product, we adapt a well established and thorough representation and rating method from the ICF. We considered a module selection problem as a strategic game with incomplete information that was represented by products' sales quantity and customer's preference. A Bayesian game was employed to model uncertainty situations regarding market environments and decided strategic equilibrium solutions for selecting modules and platforms for a universal product family. We have applied the proposed methodology to determine platforms and modules for a family of kitchen tools in a case study. Though the case study was analytic, we demonstrated that the proposed methodology can be used to determine appropriate platforms and modules in principle. Therefore, we expect that the method can help to facilitate universal product family design in uncertain market environments. Future research efforts will be focused on improving the efficiency of the method, developing cost models and design strategies for various universal product family environments, and comparing to the proposed game with other decision-making methods (e.g., collaboration, negotiation) for determining design parameters in a universal product family.

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Contact: Daniel A. McAdams
Associate Professor
Department of Mechanical Engineering
Texas A&M University
MS3123
College Station, TX 77843 USA
Phone: 979-862-7834
Fax: 979-845-3081
Email: dmcadams@tamu.edu

Dr. Moon is currently a Postdoctoral Research Associate of Mechanical Engineering at Texas A&M University. He received his Ph.D. from the Pennsylvania State University in 2008. Dr. Moon research interests focus on family and platform design for products and services; universal design; strategic and multidiscipline design optimization; agent-based decision-making; engineering knowledge engineering; and intelligent information system and management.

Dr. McAdams is an Associate Professor of Mechanical Engineering at Texas A&M University. He received his Ph.D. from the University of Texas at Austin in 1999. Dr. McAdams research interests are in the area of design theory and methodology with specific focus on functional modeling; innovation in concept synthesis; biomimetic design methods; universal design; model construction and selection for design; and complex systems modeling as applied to product design. His research has been funded by various organization including United States government research agencies and industry