A Methodology of Developing Product Family Architecture for Mass Customization

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Abstract: Mass customization, aiming at delivering an increasing product variety that best serves customer needs while keeping mass production efficiency, has recently received numerous attention and popularity in industry and academia alike. This paper presents a methodology of developing Product Family Architecture (PFA) to rationalize product development for mass customization. Systematic steps are developed to formulate a PFA in terms of functional, technical, and physical views. The diverse needs of customers are matched with the capabilities of a firm through systematic planning of modularity in three consecutive views. The development of a PFA provides a unifying integration platform to synchronize market positioning, commonality employment and manufacturing scale of economy across the entire product realization process. A case study in an electronics company is reported to illustrate the potential and the feasibility of PFA methodology.

Keywords: Product Family Architecture, Mass Customization, Product Development, Design Management.

1. Introduction

In an age when consumers demand high-quality, low-priced and customized products, the competition among firms has ceased to be strictly a price competition and is now a competition in product variety and speed to market. The current philosophy is to constantly replace old products with new versions, either an improved product or a new variation of the product. Differentiation in product variety, i.e. customization, has assumed ever increasing importance as a marketing instrument. On the contrary, alongside pursuing flexibility and quick response, manufacturers have to pursue a "dynamic stability" (Boynton and Victor, 1991). That is to keep mass efficiency to obtain the economy of scale, an advantage characterized by mass production. This oxymoron manifests a new production paradigm termed as mass customization.

1.1. Mass Customization

Mass customization embarks a new paradigm for manufacturing industries (Pine, 1993). It recognizes each customer as an individual and provides each of them with attractive "tailor-made" features that can only be offered in the

pre-industrial craft system. In the meantime, the customers can afford the products because modern mass production makes possible low product costs. Thus with mass customization, companies can outpace their competitors in gaining new customers and achieving higher margins. Figure 1 illustrates how mass production has an advantage in high volume production where the actual volume can defray the cost of huge investment in equipment, tooling, engineering, and training. However, satisfying each individual customer's needs often can be translated into higher value, whereas lower production volume cannot justify the large investments. Because mass customization allows companies to garner scale of economy through repetition, it is capable of reducing costs and lead time. Hence, mass customization achieves a higher margin and is more advantageous. With the increasing flexibility built into modern manufacturing systems and programmability in computing and communication technologies, companies with low to medium production volumes can gain an edge over competitors by implementing mass customization.

Figure 1 Mass customization: Economic implications

1.2. Technical Challenges

The essence of mass customization lies in the product developers' being able to perceive and capture latent market niches and subsequently to develop technical capabilities to meet the diverse needs of target customers. Perceiving latent market niches requires the exploration of customer needs. The capture of target customer groups means emulating competitors in either quality or cost or quick response. Keeping manufacturing costs low necessitates the appropriate development of production capabilities. Therefore, the requirements of mass customization lie in three aspects: time to market (quick responsiveness), variety (customization), and economy of scale (mass efficiency). In other words, successful mass customization depends on a balance of three elements: features, cost, and schedule.

Resulting from these requirements, a linchpin of implementing mass customization is to develop a necessary infrastructure so as to facilitate the choice of the best design alternative that simultaneously satisfies these requirements along with customers' constraints (Kotha, 1994; Lau, 1995). In order to achieve this balance, three major technical challenges have identified as follows.

(1) *Reusability/ Commonality*. Maximal amounts of repetition are essential to achieve the efficiency of mass production, as well as that in sales, marketing, and logistics. This can be attained through maximizing commonality in design which leads to reusable tools, equipment, and expertise. From a functional perspective, mass customization provides diverse end products that can be enjoyed by different customers. Customization emphasizes the difference among or the uniqueness of the products. An important step toward this goal will be the development and proliferation of design repositories that are capable of creating various customized products. This product proliferation naturally results in the continuous accretion of varieties and thus engenders design variations and process changeovers, which seemingly contradict the pursuit of low cost and high efficiency of mass production. Such a set-up, therefore, presents manufacturers with a challenge of ensuring "dynamic stability" (Boynton and Victor, 1991) which means that a firm can serve the widest range of customers and changing product demands while building upon

existing process capabilities, experience, and knowledge. Owing to the similarity over product lines or among a group of customized products, reusability suggests itself as a natural technique to facilitate increasingly efficient and cost effective product realization. By optimizing commonality across internal modules, tools, knowledge, processes, components, etc., the low cost advantage and mass efficiency can be expected so as to maintain the integrity of the product portfolio and the continuity of the infrastructure. This is particularly true in savings resulting from leveraging downstream investments in the product life-cycles, such as existing design capabilities and manufacturing facilities (Ulrich, 1995).

Although commonality and modularity have been important design practices, an emphasis on commonality is usually employed for the purpose of physical design or manufacturing convenience (Sanderson, 1991). To achieve mass customization, commonality needs to be approached from the perspective of the customers' needs or functional requirements (Suh, 1990). By grouping customers' needs according to their commonality, a set of designs can be created for the establishment of a series of product families, thus facilitating the mapping between diverse customer needs and the capabilities of the company (Tseng and Jiao, 1996).

(2) *Product platform*. The importance of product development for corporate success has been well recognized (Meyer and Utterback, 1993; Roberts and Meyer, 1991). The effectiveness of a firm's new product generation lies in its ability to create a continuous stream of successful new products over an extended time and maintain products' attractiveness to the target market niches. Toward this end, a product platform is called for to provide the necessary taxonomy for positioning different products and the underpinning structure describing the inter-relationships among various products with respect to customer requirements, competitive information, and corresponding implementing processes. A product platform in a firm has a two-fold meaning, i.e., to represent the entire product portfolio, including both existing products and proactively anticipated ones, by characterizing various perceived customer needs, and to incorporate proven designs, materials and process technologies.

In the context of mass customization, a product platform provides a technical basis for

catering to customization, managing varieties and leveraging existing capabilities. Essentially, the product platform captures and utilizes the commonality of product families and serves as a repertoire of the knowledge bases for different products. It also prevents variant product proliferation for the same set of customer requirements. The formulation of a product platform involves inputs from design concepts, process capabilities, skills, technological trends, and competitive directions (Erens and Verhulst, 1997).

(3) *Integrated product development.* Mass customization starts from understanding customers' individual requirements and ends with a fulfillment process targeting a particular customer. The achievement of time-to-market through telescoping lead times depends on the integration of the entire product development process spanning from customer needs to product delivery. Boundary expansion and concurrency are the key to the integration of the product development life-cycle from an organizational perspective. To this end, the scope of the design process has to be extended to include sales and service. On the other hand, product realization has to simultaneously satisfy various product life-cycle concerns, including functionality, cost, schedule, reliability, manufacturability, marketability, and serviceability, to name but a few. A main challenge for today's design methodologies is to support these multiple viewpoints to accommodate different modeling paradigms within a single, coherent and integrated framework (Subrahmanian et al., 1991). In other words, realization of mass customization requires not only integration across the product development life-cycle, but also the provision of a context-coherent integration of various viewpoints of the product life-cycle (Newcomb et al., 1996). It is imperative to employ a suitable product platform with unifying product and/or product family structure models to serve as a coherent integration mechanism for the common understanding of the general construction of a product, thereby improving the communication and consistency among different aspects of the product life-cycle.

2. Product Family Architecture for Mass Customization

In view of the above challenges, this paper investigates mass customization from a product development perspective. Essentially, the attempt is to include customers in the product life-cycle, particularly in the design phase, through proactively connecting customer needs to the capabilities of a company. The main emphasis is to elevate the current practice of designing individual products to designing product families. To support product customization, a Product Family Architecture (PFA) is needed to characterize customer needs and subsequently to fulfill these needs by configuring and modifying well-established modules and components (termed as building blocks). In addition, a PFA performs as an integration platform for extending the traditional boundaries of product design to encompass a larger scope spanning from sales and marketing to distribution and services.

In essence, a PFA means the underlying architecture of a firm's product platform, within which various product variants can be derived from basic product designs to satisfy a spectrum of customer needs related to various market niches. In other words, a good PFA provides a generic architecture to capture and utilize commonality, within which each new product instantiates and extends so as to anchor future designs to a common product line structure. In the context of mass customization, the rationale of a PFA resides with not only unburdening the knowledge base from keeping variant forms of the same solution, but also modeling the design process of a class of products that can widely variegate designs based on individual customization requirements within a coherent framework. Figure 2 illustrates the principle of PFA-based product development for mass customization.

Figure 2 The principle of PFA-based product development for mass customization

2.1. Structural Implications of PFA

Corresponding to different phases in the product development process (Ulrich and Eppinger, 1995; Pahl and Beitz, 1996), a PFA consists of three elements, i.e., the functional view, technical view, and physical view. As illustrated in Figure 3, various concerns of a PFA, including functionality, technological feasibility, and

manufacturability, are dealt with by particular views.

(1) *Functional view.* The functional modeling for a single product has been widely investigated, such as structural analysis (Hatley and Pirbhai, 1987) and function structuring (Hundal, 1990). The functional structure of a product consists of the functional elements (Ulrich, 1995), or called functional requirements (FRs) (Suh, 1990), and their interrelationships that involve the decomposition and/or dependency (Pahl and Beitz, 1996). In the context of product families and mass customization, the functional structure of a PFA exhibits the product line of a firm which manifests the customers' perceptions on its product spectrum (product offerings). The functional merit of a PFA is judged by the capability of its product line structure for customer recognition related to target market niches. A product line structure is therefore referred to as the underlying patterns of customer requirements captured by the product portfolio. More specifically, the functional view of a PFA embodies a product line structure in terms of different customer groups, the FRs and their relative importance/priority for every customer group, and the classification of FRs instances (FRs*) for the customers within each customer group. While incorporating specific product strategies and business vision, product line structuring usually excludes engineering considerations such as costs and process planning. More issues related to the functional modeling of a PFA include customer segmentation, product strategies, competition analysis, technological trends, and so on.

(2) *Technical view.* Corresponding to each customer group identified in the functional view of a PFA, the technical view reveals the application of a technology (i.e., solution principle) to a product design and describes the product design by its modules and the modular structure. A modular structure is referred to as the combination of modules to configure modular products (Kohlhase and Birkhofer, 1996). It describes the subdivision of end products into smaller units and the interconnections (interrelationships) between modules (Pahl and Beitz, 1996), e.g., a circuitry topology in electronic product design. In technical modeling, modules and modular structures are defined in terms of the design parameters (DPs)

corresponding to specific FRs (Suh, 1990) instead of physical components and assemblies. The purpose is to highlight differentiation (variety) in product design resulting from different solution technologies applied to meet diverse customer needs. The variation (variety) resulting from manufacturing concerns is dealt with by the physical view of the PFA. Issues regarding the technical modeling of a technological solution include documenting DPs and the mappings from FRs to DPs, determining design modules by minimizing design coupling (Suh, 1990), and establishing modular structures for design configuration.

(3) *Physical view.* The physical view is similar to Eren et al.'s physical model (1997). This physical view represents product information by a description of the physical realization of a product design and is strongly related to the construction of the product. Existing process capabilities pose constraints on this realization to guarantee easy manufacturing and assembly operations without compromising the cost and quantity constraints, that is to keep the economy of scale. More specifically, the physical model consists of various types of components and assemblies (CAs) in order to realize different technological solutions in the technical view. In addition to the mapping relationships of FR-DP-CA, an important concern associated with the physical view is the economic evaluation of the granularity trade-off among various CAs options according to available process capabilities of a firm. This is approached by identifying suitable component clusters, or chunks as called by Pimpler and Eppinger (1994), and assembly levels across all the products (families) by incorporating volume and cost concerns. Moreover, different component modularity strategies, such as component-swapping, component-sharing, and bus modularity (Ulrich and Tung, 1991), should be explored in determining the configuration structures of end products.

Figure 3 Structural implications and multiple views of a PFA

2.2. Mappings Between the Views of PFA

While corresponding to and supporting different phases of product development using three types of product model, the PFA integrates several business functions in a context-coherent framework. This is manifested by the mappings

between three views of the PFA (Figure 3). Various types of customer needs (customer groups) are mapped from the functional view to the technical view characterized by solution principles (DPs and modular structures). Such a mapping embodies design activities. The mapping between the technical view and the physical view reflects considerations of manufacturing and logistics, where the modular structure and technical modules in terms of DPs are realized by the physical modules in terms of components and assemblies through incorporating assessments of available process capabilities and the economy of scale. The sales and marketing functions involve the mapping between the physical view and the functional view, where the correspondence of a physical structure to its functionality provides necessary information to assist negotiation among the customers, marketers, and engineers, e.g. facilitating request-for-quotation (RFQ).

2.3. Functional Variety and Technical Variety

While facilitating developing superior products, design for manufacturability methodologies usually address a single product (Prasad, 1996). Beyond such limitation, a new class of methodology for product variety is required to optimize product lines across families and generations (Fujita and Ishii, 1997). In order to optimize product variety, however, it is necessary first to classify the types of variety, particularly in terms of the requirements of mass customization, and then develop pertinent design strategies.

Product variety is defined as the diversity of products that a production system provides to the marketplace (Ulrich, 1995). In this paper, we assert two types of variety, namely the functional variety and the technical variety. The functional variety is used broadly to mean any differentiation in the attributes related to a product's functionality from which the customer derives a benefit. On the other hand, the technical variety is referred to as diverse technologies, design methods, manufacturing process, components and assemblies, etc., which are necessary to achieve some functionality of a product required by the customer. While the functional variety is often related to the customer satisfaction, the technical variety usually involves the manufacturability and costs.

Even though the two types of variety have some correlation in product development, they result in two different design strategies. Since the functional variety directly affects customer satisfaction, this type of variety should be encouraged in product development. Such a design for "functional" variety strategy aims at increasing functional varieties and manifests itself through vast research in the business community, such as product line structuring (Sanderson, 1995). On the contrary, design for "technical" variety tries to reduce technical varieties so as to gain cost advantages. Under this category, research includes design for variety (Ishii et al., 1995a; Martin and Ishii, 1996; 1997), design for postponement (Feitzinger and Lee, 1997), design for technology life-cycle (Ishii et al., 1995b), and function sharing (Ulrich and Seering, 1990), etc.

2.4. Modularity and Integrity in PFA

The concepts of modules and modularity are central in the description an architecture (Ulrich, 1995) and design for mass customization (Tseng and Jiao, 1996). While a module is a physical or conceptual grouping of components that share some characteristics, modularity tries to separate a system into independent parts or modules which can be treated as logical units (Newcomb et al., 1996). To deal with the dilemma of variety and scale, the PFA achieves its modularity from multiple viewpoints, including functionality, technologies, and physical structures. Correspondingly, there are three types of modularity involved in the PFA, i.e., functional modularity, technical modularity, and physical modularity.

In module identification, interactions between modules should be minimized while the interactions of components within a module may be high (Ulrich, 1995). Therefore, each type of modularity is characterized by a particular measure of its interactions. In functional modularity, the interaction is resembled by the similarities of FRs and/or their instances. The exploration of similar customer requirements lies only in the functional view, which is independent of the other two views, that is, to be solution-neutral. In the technical view, modularity is mostly determined by the technological feasibility of design. The interaction is thus judged by the coupling of DPs (Suh, 1990) regardless of their physical realization in manufacturing. The manufacturability is a major concern in physical

modularity, where the interaction is measured by engineering costs derived from available process capabilities and estimated volume.

In response to the reusability/commonality challenge of mass customization (see section 1.2), in a PFA, the complicated modularization problem is decomposed into three independent modularity views. While different issues regarding different business functions are dealt with by specific views of a PFA, the integrity of product family design is maintained by the mapping mechanisms between different views.

2.5. Class-Member Relationships for Variety Representation

In addition to dealing with different types of variety through systematic planning of modularity in three consecutive views, a PFA organizes and represents a variety of objects in different views using class-member relationships. For three types of objects corresponding to the three views, i.e., functional, technical and physical modules, the object varieties result from two layers. First the objects differentiate in terms of their attribute variables (e.g., FRs and DPs). Different sets of variables characterize diverse types of objects. Then, for each type of objects (class) with a specific set of variables (class attributes), varieties can further result from different instances (members) of particular variables. Such a representation using class-member relationships reveal the sources and migration of varieties involved in different views of a PFA. Figures 4 and 6 illustrate the application of class-member relationships to variety representation.

3. Development of Product Family Architecture

3.1. Assumptions — Industrial Products

While mass customization is discussed mostly for consumer products (Baker, 1989; Kolter, 1989; Sanderson, 1995; Meyer and Utterback, 1993), here we assert the necessity to emphasize on those industrial products, such as power supply products, which pose a few challenges on both design and manufacturing, as well as marketing. The assumptions associated with the market and engineering practice for industrial products are observed next.

The market for industrial products has the following features which make customer requirement analysis easier:

(1) Customers of industrial products usually have more knowledge of products than those of consumer products. Therefore, customers of industrial products can offer more definite information concerning their needs.

(2) In the market of industrial products, purchase decision making is conducted by concrete factors such as product performance and product costs rather than abstract factors such as aesthetic and ergonomic criteria.

(3) Since the number of customers is comparatively limited and customers can often be specified in the market for specific industrial products, a survey of market needs can easily be conducted with acceptable accuracy.

The engineering practice of industrial products manifests itself through more incremental than innovative development (Pahl and Beitz, 1996). That is, evolutionary product development is frequently adopted in practice to evolve from existing products, instead of designing a product from scratch. The advantages lie in the utilization of the learning from historical data, warranty information, customer feedback, installation, and service records, etc., so as to enhance product features and reduce development efforts.

3.2. Functional Modeling Through Customer Requirement Analysis (Phase I)

In the functional view of a PFA, a rigorous product line structure depends on a gestalt analysis of product requirements, which starts from the investigation of customer profiles followed by explicating the underpinning patterns of customer needs. The following steps are suggested for systematic analysis of customer requirements.

3.2.1. Inductive FRs formulation based on existing products

The FRs formulation lies in the customer and functional domains of a design process (Suh, 1990) and starts from the definition of a set of aggregate FR features or variables with respect to existing product portfolio. Semantics methods such as the KJ method (Affinity diagram) and MPM (Multipickup method) are the basis for discovering the underlying facts from affective language (Shiba et. al, 1993). The FRs formulation aims at developing a FR hierarchy which consists of FR variables and their

interrelationships. The formulation of FR interrelationships can apply knowledge acquisition processes often used in the development of AI systems (Lu and Tchong, 1990). Note that the formulated FRs are generic to the entire product portfolio, i.e., all the customers in the related market.

3.2.2. Deductive FRs refinement based on product strategies

To modify the above FRs formulation induced from existing products, product strategies are proactively assessed by considering competition, technological migration, market trends, and so on. This deductive stage is very important for defining product line structures in PFA development in order to enhance the marketability of product offerings. Systematic methods for incorporating these strategic axes into product design have been suggested by Aoussat et al. (1995).

3.2.3. Collection of demand data and FRs instantiation

The most important point in decision making of product development is whether or not the product meets the present needs of the market. Therefore, in this paper, the following survey is conducted for exploring customer profiles:

- (1) Check the number of planned products for each customer, including forecasted volume;
- (2) Check specific product attributes (FRs) according to the above formulated FRs for every customer;
- (3) Check the desired value (FR instance) and importance level (priority) for each attribute (a particular FR variable) selected in (2).

Based on the FR hierarchy formulated above, the functional specifications of existing products can be mapped into various FRs instances to represent specific products. Due to diverse customer specifications, null can be an acceptable value for specific FR variables. By mapping, useful historical data and domain knowledge are incorporated into and represented by FRs instances.

3.2.4. Customer grouping

While the formulated FRs are generic to all the customers, different customer groups may require different sets from these FRs for their particular applications. Therefore, the FRs need to be categorized into different sets to

characterize specific customer groups. This is consistent with various product series in catalog design targeting diverse market niches (Meyer and Utterback, 1993). Since customer profiles have been projected and instantiated by a population of FRs instances, a pareto analysis can be employed to extract key FRs for characterizing different customer groups. These key FRs can be regarded as meta-FRs (Tseng and Jiao, 1997a) that are a subset of generic FRs formulated above. The considerations in pareto analysis include the relative importance of FRs for different customers and the demand volumes of every customers. Finally, different sets of FR variables are formulated for various customer groups.

3.2.5. Functional classification for each customer group

Within each customer group represented by a particular set of FR variables, even though all the customers share the same set of FRs, various functional varieties could result from different desired values for a particular FR variable (different FR instances). A classification of various FRs instances for a particular set of FR variables is referred to as functional classification.

In our research, the fuzzy cluster analysis (Gu and Dubuisson, 1990; Zimmermann, 1991) is employed, in which similarities of customer needs (i.e., FRs instances) are evaluated. As a measure in the cluster analysis, the distances among the desired values for product attributes (i.e., FRs) are used. Suppose there are m customers (products) in a particular customer group (product family), which is characterized by n product attributes. The distance $d_{j,j+1}$ between customer j 's ($\forall j=1,2,\dots,m$) desired value $FR_{i,j}^*$ and customer $j+1$'s desired value $FR_{i,j+1}^*$ is defined for this customer group (product family) with product attribute i ($\forall i=1,2,\dots,n$) as follows:

$$d_{j,j+1} = \sqrt{\sum_{i=1}^n \left(w_i \left(\frac{FR_{i,j}^* - FR_{i,j+1}^*}{FR_i^*} \right)^2 \right)}, \quad (1)$$

where $FR_i^* = \frac{\sum_{j=1}^m FR_{i,j}^*}{m}$ is the standard value

of product attribute i , introduced for evaluating products' attribute values having different units on the same scale, and w_i is the weighting coefficient

of product attribute i where a greater value is given to a more important product attribute with respect to purchase decision making. In practice, for more consistent and rational weighting, the analytic hierarchical process (AHP) method (Satty, 1991) can be employed.

A few articles have addressed the algorithms for FCM clustering analysis (Gu and Dubuisson, 1990). Among them, a common one, namely the fuzzy C-means (FCM) clustering algorithm is adopted in this study. Detailed descriptions on fuzzy clustering analysis are presented by Zimmermann (1991).

The functional classification procedure by the FCM cluster analysis is completed when the variation of the desired values of the product attributes (that is, the variation of $d_{j,j+1}$) in a cluster reaches the upper limit or when the total number of customers (products) reaches the lower bound.

3.2.6. Determination of target FR values for product family planning

Through functional classification, similar customers in terms of their desired-values for a FR variable comprise a cluster which is characterized by a representative center vector (Zimmermann, 1991). Usually, several clusters are formed and necessitate a product family design, where each product variant aims at each cluster of customers. In planning such a product family design, the target value for a FR variable can be determined based on domain knowledge as a result of understanding the characteristics of the clustered class. Usually, various desired FR values of customers in the same cluster are averaged to obtain a representative FR value which is used as the target FR value for a planned product variant. Since mostly more than one FR variables are involved, the representative FR values should be derived from the center vector of a particular cluster, thus resulting in a vector of target values for the planned product variant with multiple FR features. Similarly, a set of weights for planned FR variables can be obtained based on the results of functional classification.

3.2.7. Representation of the functional view of a product family

In order to describe both a family and its product variants in a single formalism, a combined

decomposition/classification tree (DCT) is adopted to represent the functional view of a product family from an abstract level to individual instances. There are two types of tree structure in a DCT. One is the decomposition tree (*and* tree) adopted to represent the FR hierarchy, where each node represents a FR with its sub-FRs breakdown. The links between a child node and its parent node resemble "a-part-of" relationships. The other one is the classification tree (*or* tree) used to describe the variants of every FRs. The classification tree lies in the lowest level of a DCT, indicating different instances of every FR variable. These instances exhibit various variants of each FR variable and are denoted by the leaves of a DCT. The child-parent relationship is presented as "a-kind-of" link, i.e., a class is a kind of its superclass. Figure 4 shows the structure of a general DCT, where a node denotes a FR variable while a leaf represents an instance of a FR variable. In a DCT, functional specifications of a product family can be described at any level of the abstraction along the FR hierarchy.

Inherently, a DCT can exhaustively describe all product differentiation in terms of functional variety for a product family. The functional specifications can be described using a vector form and class-member relationships. At a particular level of the abstraction across the decomposition tree, a set of nodes comprises a FR vector denoting the functional specification of a product family, where each node characterizes a common feature of the product family (a class). For example, the functional specification of a product family can be depicted by $\overline{FR}_{Product_Family} = \{FR11, FR121, FR122, FR2, FR31, FR32\}$, whereas the specific specification of a product variant within this family (a member) is an instance of this FR vector by trimming the classification tree, e.g., $\overline{FR}_{Product_Variant} = \{V11_1, V121_2, V122_3, V2_4, V31_1, V32_3\}$.

Figure 4 The and/or tree representation of the functional view of a product family

In summary, the functional modeling of a PFA sets the targets for product family design. Customer grouping determines the type of a target product family, where different customer groups are projected to different product families. Functional classification of a particular customer

group gives rise to the target product variants within the product family for this customer group.

3.3. Technical Modeling Through Modularizing Technological Solutions (Phase 2)

The technical modeling aims at exploring the modularity underlying various available technologies applied to existing products in response to specific customer groups. For a particular customer group identified in *Phase 1*, the following procedures are suggested for modularizing the technological solutions of product family design for this customer group.

3.3.1. DPs formulation

According to axiomatic design theory (Suh, 1990), decision structure inherent in the design process involves the definition of DPs as an explicit means to satisfy a progressively decomposed set of requirements and to provide detailed, concept-level associations of requirements to available options. Given the generic FRs formulated in *Phase 1* and the solution technologies applied to existing products, DPs are identified based on their ability to fulfill FRs. Processes such as the zigzagging decomposition process proposed by Suh (1990) are very useful in identifying these parameters for individual products. All the DPs and their interrelationships are represented by a DP hierarchy.

3.3.2. Documenting FR-DP mapping relationships

Design is often defined as the creation of synthesized solutions through mapping between FRs and DPs. These mapping relationships can be best depicted by a design matrix linking a FR hierarchy and a DP hierarchy (Suh, 1990), i.e., $[FR]_m = [A]_{m \times n} [DP]_n$, where $[A]_{m \times n}$ is the design matrix. An element of the design matrix, $a_{ij} \in [A]_{m \times n}$, indicates the correspondence from FR_i to DP_j . The result of this step is such a design matrix.

3.3.3. Exploring technical modularization

In practice, design matrices are often coupled, referred to as functional coupling (Johannesson, 1997). The technical modularization tries to

decompose such couplings into smaller logic units, i.e., design modules. Given a design matrix with 0-1 elements denoting the corresponding FR-DP relationships, matrix decomposition techniques (Pimmler and Eppinger, 1994) can be applied to induce element cells, each of which indicates what-how relationships between a set of FRs and a set of DPs. While different cells have looser coupling, infra-cell elements comprise a cluster of FRs and corresponding DPs with distinct boundary from other cells. As a result, FR-DP cells or clusters in fact indicate the boundaries among different design modules. In addition, the inter-cell elements indicate the interfacing relationships between different clusters (modules), which often results in tradeoffs in design decision making. Furthermore, this module analysis can be performed at any level of abstraction as appropriate along the FR and DP hierarchies. Figure 5 illustrates this idea.

Essentially, a design matrix's decomposition into modules is performed by converting the matrix into block-diagonal or lower-triangular form. While other techniques exist for computing partitions of a set, the matrix decomposition technique has a beneficial visual interpretation. The algorithm developed by Kusiak and Chow (1987) is employed here because of its versatility in handling symmetric, asymmetric, and non-square matrices. The algorithm is briefly explained as the following (Newcomb et al., 1996):

Step (1): Counter k is initialized to 1.

Step (2): Select any row i of incidence matrix $A^{(k)}$ ($A^{(k)}$ denotes matrix A at iteration k) and draw a horizontal line through it.

Step (3): For each element of "1" on the interaction with the horizontal line, draw a vertical line through columns.

Step (4): For each element of "1" crossed by the vertical line, draw a horizontal line through the rows.

Step (5): Repeat *Steps (3) and (4)* until no crossed elements of "1" remain. All double crossed elements of "1" form a module.

Step (6): Transform the incidence matrix $A^{(k)}$ into $A^{(k+1)}$ by removing the rows and columns corresponding to the horizontal and vertical lines drawn in *Steps (2) through (5)*.

Step (7): If matrix $A^{(k+1)} = \emptyset$, stop; otherwise set $k = k + 1$ and goto *Step (2)*.

Figure 5 Design matrix decomposition for technical modularity

3.3.4. Representation of design modules

The representation of a design module (building block in terms of DPs) involves both its functional and structural aspects. A FR-DP tuple is suitable to capture the correspondence between a design module and its intended function. In addition, a class-member relationship is applicable to characterize the differentiation of such building blocks derived from either the type (class) of a FR-DP mapping or different instances (members) of a particular mapping. Therefore, a building block class (BB_k) is defined by FR_k and DP_k that are implicated by its type of mapping relationship ($FR_k - DP_k$), that is, $BB_k \sim \{FR_k; DP_k\}$. An instance of this building block class, BB_{k-i} , is determined by a specific value (instance) of FR_k and/or DP_k defined by a building block class BB_k , i.e., $BB_{k-i} \sim \{FR_{k-i}; DP_{k-i}\}$, where k is the index of a particular building block type (class), and i indicates an instance of DP_k (i.e., DP_{k-i}) and its performance value of FR_k (i.e., FR_{k-i}). Figure 6 illustrate such a representation of building blocks.

Figure 6 Representation of a building block class and its instances

3.3.5. Establishing modular structure

Once design modules in terms of DPs have been identified, the modular structure needs to be revealed to represent the overall schematic of arranging these design modules for design configuration. In establishing a modular structure, the working principle of a solution technology is of particular concern in determining how to fit design modules into the structure. Usually, such a work heavily depends on sophisticated domain knowledge.

In summary, the technical modeling aims at identifying design modules for designing a product family by considering the technological feasibility, along with a modular structure for configuration according to these modules. Such a technical model characterizes the mechanism of deriving product variants from a product family.

3.4. Physical Modeling Through Economic Evaluation of Physical Modules (Phase 3)

In physical modeling, the technical modularity is realized in terms of physical product structures. Components and sub-assemblies (CAs) are determined according to design modules identified in technical modeling. Manufacturing concerns, such as manufacturability, costs, volume, and schedule, are taken into account in such a transformation of technical modularity to physical modularity. The overall configuration structure of product families is also formulated, where various product variants can be derived from diverse CAs according to specific configuration rules and schematics. The following steps are suggested for physical modeling.

3.4.1. Determining physical instances of design modules according to available process capabilities

For each design module identified in Phase 2, the corresponding components and assembly structures can be determined according to available process capabilities and with reference to existing products. The major concern is the manufacturability implicated by the production systems of a firm.

3.4.2. Formulating candidate physical modules

Repeat the above procedure for every design modules of planned product families. Thus all possible physical modules in terms of CAs can be obtained in order to produce all planned product variants of product families. In other words, a design module (building blocks in terms of DPs) is possible to be realized by more than one physical modules (building blocks in terms of CAs). The next issue is to select suitable physical modules for specific design modules through economic evaluation of these physical modules.

3.4.3. Measuring the performance of a physical module

Various models for expressing customers' expectations on products have been presented (Shocker and Srinivasan, 1979; Kumar and Sudharshan, 1988). In this research, we adopt utility analysis technique (Yoshimura and Takeuchi, 1994).

As shown in Figure 7, the utility U_{ij} of a physical module i for its functional attribute j (i.e., FR_{ij}) responses to the value of DoS_{ij}

(degree of satisfaction), expressing the distance (i.e., discrepancy) of the module's performance value FR_{ij}^* away from its target value FR_{ij}^T determined in Phase 1. When the module performance has a negative value of DoS_{ij} and is close to the target value, the utility U_{ij} increases. When the performance becomes more preferable than the desired value, that is, $DoS_{ij} > 0$, the change of increase in U_{ij} becomes smaller. A widely-used function resembling the response curve shown in Figure 7 is as follows:

$$U_{ij} = \frac{1}{\pi} \tan^{-1} \{ \alpha (DoS_{ij} + \beta) \} + 0.5, \quad (2)$$

$$DoS_{ij} = \lambda \frac{FR_{ij}^* - FR_{ij}^T}{FR_{ij}^*}, \quad (3)$$

Where α and β are coefficients obtained by the regression analysis of existing products, $\lambda = 1$ if the functional attribute FR_{ij} is more preferable when the value of DoS_{ij} increase (the-more-the-better), and $\lambda = -1$ if the functional attribute FR_{ij} is more preferable when the value of DoS_{ij} decrease (the-smaller-the-better).

The overall utility U_i of a module i is obtained by composing all individual utility measures U_{ij} for each attribute j . The relative importance of each functional attribute j of module i , noted as w_{ij} , should be considered in composite utility U_i as follows:

$$U_i = \prod_{j=1}^n (U_{ij})^{w_{ij}}, \quad (4)$$

where n is the total number of functional attributes for determining the performance (U_i) of physical module i .

In Eq. (4), when importance level w_{ij} is large for high individual utility U_{ij} , the composite utility U_i has a large value close to 1, whereas U_i has a small value close to 0 when w_{ij} is large for low individual utility U_{ij} . For low w_{ij} , U_i always has a value close to 1.

The composite utility U_i defined in Eq. (4) expresses the performance evaluation of a

physical module with multiple functional attributes. When every attribute takes on a value close or superior to the target value, the module's utility has a value close to 1. On the other hand, the lower the level is for each attribute value compared with the target value, the further the module's utility value decreases from 1 and, of course, the value is smaller.

Since modularity can happen at different levels of abstraction, it is necessary to formulate the utility value for a group of modules (e.g., the utility of a product family) as the follows:

$$U = \frac{\sum_{i=1}^m (V_i U_i)}{\sum_{i=1}^m V_i}, \quad (5)$$

where V_i denotes the estimated demand volume for module i and m is the total number of modules of different types. In Eq. (5), it can be revealed that a high volume of modules with large utility levels exerts positive effect on the group utility value.

Figure 7 Performance evaluation based on the utility of a product attribute (Yoshimura and Takeuchi, 1994).

3.4.4. Estimating the cost of a physical module

In this research, we adopt a pragmatic approach to cost estimation based on standard time estimation (Tseng and Jiao, 1997b). Here the CAs of a physical module serve as the cost-related design features (CDFs) to retrieve and compose the process plan for the module based on a set of standard routings identified beforehand. Start with this "virtual" process plan, the standard time can be estimated for producing this module according to time-estimating relations (TERs) established earlier. Then the estimated cost of this module can be derived from cost-estimating relations (CERs) that are formulated before by allocating overhead costs to the standard times established from existing products.

3.4.5. Economic evaluation of building blocks

The purpose of economical evaluation is to position various building blocks according to their contribution to maintaining the economy of scale and providing "functional variety". In other words, the "common denominators" (Tseng and Jiao, 1996) should be maximized only for those building

blocks that are both utility-important to the customers and cost-effective.

The evaluations against technical and economic criteria presented above, lead to a pairwise overall ratings for building blocks. For illustrative simplicity, here we present a pragmatic tool, C-U plot, adapted from Ishii's (1995a) I-C plot. For more rigorous solving of this multi-attribute design evaluation problem, we have developed a fuzzy ranking approach using information-content measure (Jiao and Tseng, 1998).

In order to be consistent with $\forall U_i \in [0,1]$, the cost estimates of modules are first normalized, and thus each cost estimate is transformed to a relative cost measurement ranging from 0 to 1. An assessing diagram with the utility measurement as the abscissa and the relative cost measurement as the ordinate can be used, called a C-U plot, as illustrated in Figure 8.

As shown in Figure 8, there are five different regions of evaluation results in a C-U plot, from which useful managerial implications can be derived. (1) A building block falling into region A, where U is large and C is small, indicates a cost-effective design with high customer preferring utilities. Such building blocks is referred to as a common building block (CBB), which performs as the stability-enabler for a PFA. It is therefore meaningful to maximize the reusability of CBBs in product family development. (2) Region B represents those building blocks with high customer utilities as well as large costs. These determinant building blocks, called variant building blocks (VBBs), dominate product differentiation and act as the dynamic drivers for a PFA. (3) Building blocks in region D, called selective building blocks (SBBs), are less useful for customer choices but have low costs. Thus, low priority should be given to these SBBs. (4) Building blocks belonging to region C are characterized by high costs without much customer perceived utilities. These building blocks should be discarded to avoid non-cost-effective differentiation. (5) When a building block falls into region E, the design need to be improved towards region A.

Figure 8 The C-U plot for building block evaluation (Modified from Ishii et al., 1995a)

3.4.6. Establishing the configuration structure for each product family

With various physical modules identified for each product family, a configuration structure needs to be established for end product configuration. A configuration structure of a product family describes how various product variants are derived from the combination (configuration) of the physical modules and their interconnections across different levels of assembly. In addition to the physical modules and assembly hierarchies developed through above steps, the technical modular structure developed in Phase 2 reveals the working principles for guiding end product configuration.

Different from the bill-of-material (BOM) type (configuration) hierarchy widely used for a single product modeling, a polyhierarchical node-arc graph (Kohlhase and Birkhofer, 1996) can be used to describe the configuration structure for a product family. Figure 9 shows such a graph representation of the configuration structure for a product family, which can be considered as the adaptation and extension of BOM structure to describe a product family. The nodes depict the objects and the arcs indicate the interrelations between the nodes. While the hierarchical levels conform to physical assembly levels from components up to end products, the numbers attached to the arcs represent the number of objects required for upper level assemblies. More important, such a configuration structure describes the realization of product differentiation in terms of physical product structures and the production of varieties derived from configuring building blocks.

Figure 9 A graph representation of the configuration structure for a product family

4. A Case Study

A power supply company under our investigation offers various products covering a range of more than 1,200 varieties. Because of the growing varieties, the company is constantly challenged to achieve responsiveness, flexibility, and low costs. There is a significant amount of engineering expenses for meeting diverse customer applications. The PFA methodology has been applied to the company's endeavor towards mass customization.

As a type of industrial product, a power supply is a key component in electronic products,

such as telephone switching PBX, stereo equipment, computers and instrumentation, etc. Figure 10 shows examples of power supply products.

Figure 10 Various types of power supply products

4.1. Phase 1: Functional Modeling of PFA

First of all, the general FRs regarding power supply design are identified and formulated in a hierarchical form through comprehensive interviews with domain experts (Tseng and Jiao, 1997a). For illustrative simplicity, here we only give FRs formulation for the low power AC/DC converters (Table 1). This category of low power AC/DC converters actually results from the customer grouping procedure described in section 3.2.4. Other customer groups include, for example, medium power AC/DC converters and DC/DC converters. Different customer groups have quite different sets of FRs in power supply sector.

According to these FRs, more than 300 existing product models belonging to the customer group of low power AC/DC converters are instantiated into various FRs instances. Since these FRs instances vary widely due to diverse desired values and/or ranges for specific FRs, the functional classification procedure is applied to group similar customer specifications into one cluster and determine the target values for every clusters of functional specifications. Figure 11 illustrates the results of functional classification, where different target values for each FR variable are determined for subsequent product family development based on experts' knowledge as a result of understanding the characteristics of the clustered classes. For example, one of the target value of *total power* (Figure 11) is set as 40W, resulting from clustering similar customer requests, such as 35W, 32.5W, 41W, 38W, etc. In the functional classification, different priorities of FRs and the volumes of every customer requests are taken into account. For instance, the *total power* is of paramount importance among all the FRs.

Table 1 An example of the FR hierarchy for power supplies

Figure 11 Representation of the functional view of a PFA for power supply products

4.2. Phase 2: Technical Modeling of PFA

The available technologies for power supply are investigated at this stage. Figure 12 gives two examples of solution principle, which is often termed as topology in power supply design (Brown, 1994). According to all the target functional specifications of the customer group and considering technological trends and existing process capabilities, one of the many topologies, i.e., the fly-back topology, is selected as the solution technology, which is very suitable for low power AC/DC converters (Brown, 1994).

Once the solution technology has been determined, the DPs are then formulated with respect to the FRs. Table 2 shows the results of DPs formulation. The FR-DP mapping relationships are documented in the left half of Figure 13. Following the matrix decomposition procedures presented in section 3.3.3, the design matrix is decomposed into cells (right half of Figure 13), from which design modules are induced (Table 3). An example of building block representation is given in Table 4. Figure 14 illustrates a higher level modular structure revealing the working principle of design and highlighting the arrangement of different design modules (building blocks in terms of DPs) for design configuration. More specifically, it determines the way in which the power holding parts of a power supply is configured.

Figure 12 Two different topologies for power supply design

Table 2 An example of the DP hierarchy for power supplies

Figure 13 Design matrix decomposition for technical modularity

Table 3 Power supply design modules

Figure 14 An example of a modular structure for power supply design

4.3. Phase 3: Physical Modeling of PFA

For illustrative simplicity, one of the many building blocks, the transformer module, is adopted here to demonstrate the physical modeling of PFA. The design module of transformer (Table 3) is described by its DPs and intended FRs as shown in the upper half of Table 4. Considering available resources and existing process capabilities of the company, the DPs are instantiated as physical components and/or assemblies. Table 4 gives simplified results, where candidate physical modules of the transformer are

listed by their physical attributes (the type and size of the core) and expected performances (output power).

Four types of target performance have been determined in *Phase 1*, i.e., 25W, 40W, 60W, and 100W. The performance of each physical module is evaluated against these targets according to the procedure introduced in section 3.4.3. In our case, the utility function taking on the form of Eq. (2) uses the coefficients of $\alpha = 30$ and $\beta = 0.2$ that are empirically obtained through regression analysis. Then the cost for each alternative module is estimated according to the procedure of section 3.4.4.

Figure 15 presents the results of economic evaluation, from which different modules are selected for different design strategies in the product family design. As shown in Figure 15, EEL-C and MPP-C are identified as common building blocks while EEL-D and MPP-D are variant building blocks. However, all the other modules drop in non-preferable regions, thus they are discarded from product family design.

Similar procedures are conducted for all design modules, and thus yielding various types of components and assemblies. With reference to the modular structures in the technical view, the configuration structure of product family design is established with respect to identified building blocks. Table 5 presents a part of a simplified configuration structure for a specific product family, where the configuration structure is given in a tabular form to circumvent tedious graph representation. In practical production systems, a part coding scheme is usually used to identify different component and sub-assemblies for modules and/or end products. As illustrated in Table 5, different indented levels conform to the assembly levels from component to sub-assemblies and to end products. Various building blocks (those with its part code bolded in Table 5) can be either a component or a sub-assembly and are shared at different levels across the entire product family.

Table 4 An example of building blocks in power supply design

Figure 15 An example of the economic evaluation of building blocks

Table 5 A tabular form of the configuration structure for a product family

5. Concluding Remarks

As the new frontier of business competition and production paradigm, mass customization is emerging high-up on the agenda. This paper presents a methodology of developing Product Family Architecture (PFA) to rationalize product development for mass customization. Systematic steps are developed to formulate a PFA in terms of functional, technical, and physical views. The diverse needs of customers are matched with the capabilities of the firm through systematic planning of modularity in three consecutive views. The PFA provides a generic architecture to capture and utilize commonality, within which each new product instantiates and extends so as to anchor future designs to a common product line structure. The rationale of the PFA resides with not only unburdening the knowledge base from keeping variant forms of the same solution, but also modeling the design process of a class of products that can widely variegate designs based on individual customization requirements within a coherent framework. In addition, the PFA performs as a unifying integration platform to synchronize market positioning, commonality employment and manufacturing scale of economy across the entire product realization process. Preliminary results in a local company have shown some promising benefits of developing PFA for mass customization.

Product family is a well accepted practice in industry. Group Technology (GT) traditionally explores and utilizes similarities in manufacturing and production with focus on the component level in the process domain. The emphasis of this paper is at the product level in design domain. To facilitate developing common building blocks and product families, the established methods in GT such as clustering and inductive learning are applicable. It is believed that we can get additional benefits in productivity improvement and designing manufacturing systems by propagating the PFA methodology to the downstream process domain. We are now at an early stage in this research. So far, most of our work is concentrated on the up-front effort of design, i.e., the customer, functional and physical domains of design, where we believe a good design should start.

The PFA methodology can pose significant impacts on the organizational structures in terms of new methods, education, division of labor in marketing, sales, design and manufacturing. The

development of a PFA can lead to a redefinition of job as we witnessed in our case studies. For instance, the Sales & Marketing Department will be in a position to map customer requirements to specifications of suitable products under the umbrella of a PFA. In other words, Sales & Marketing may start to work on the configuration of building blocks. In a sense, this is a type of design work which is traditionally carried out in the Design Department. By doing so, the Design Department can focus on design of the PFA in response to technological changes, manufacturing process evolution or customer needs changes. Manufacturing will focus on the reuse of tooling, setup, process knowledge, etc. according to the building blocks of a PFA, along with interface assessment and configuration optimization.

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References

Aoussat, A., Christofol, H., Auvray, L. and Le COQ, M. (1995) Competitive Analysis and Product Design, *Proceedings of 1995 International Conference on Engineering Design*, Praha, pp. 879-884.

Baker, M. (1989) Marketing: A New Philosophy, *The Quarterly Review of Marketing*, Vol. 14, No. 2, pp. 1-4.

Boynton, A. C. and Victor, B. (1991) Beyond Flexibility: Building and Managing the Dynamically Stable Organization, *California Management Review*, Vol. 34, No. 1, pp. 53-66.

Brown, M. (1994) *Power Supply Cookbook*, Butterworth-Heinemann, Boston.

Erens, F. and Verhulst, K. (1997) Architectures for product families, *Computers in Industry*, Vol. 33, No. 2-3, pp. 165-78.

Feitzinger, E. and Lee, H. L. (1997) Mass Customization at Hewlett-Packard: The Power of Postponement, *Harvard Business Review*, Vol. 75, No. 1, pp. 116-121.

Fujita, K. and Ishii, K. (1997) Task Structuring toward Computational Approaches to Product Variety Design, *Proceedings of ASME Design Engineering Technical Conferences*, DETC97/DAC-3766, Sacramento, CA, USA.

Gu, T. and Dubuisson, B. (1990) Similarity of Classes and Fuzzy Clustering, *Fuzzy Sets and Systems*, Vol. 34, No. 2, pp. 213-221.

Hatley, D. J. and Pirbhai, I. A. (1987) *Strategies for Real-Time System Specification*, Dorset House, New York.

Hundal, M. S. (1990) A Systematic Method for Developing Function Structures, Solutions and Concept Variants, *Mechanisms and Machine Theory*, Vol. 25, No. 3, pp. 243-256.

Ishii, K., C. Juengel and C.F. Eubanks (1995a) Design for product variety: key to product line structuring, *Design Engineering Technical Conference*, DE-Vol.83, Volume 2, 499-506, ASME.

Ishii, K., Lee, B. H. and Eubanks, C.F. (1995b) Design for Product Retirement and Modularity based on Technology Life-Cycle, *Manufacturing Science and Engineering*, MED-Vol. 2-2/MH-Vol. 3-2, pp. 921-933, ASME.

Jiao, J. and Tseng, M. M. (1998) Fuzzy Ranking for Concept Evaluation in Configuration Design for Mass Customization, Working Paper, IEEM, Hong Kong University of Science and Technology.

Johannesson, H. L. (1997) Application of Interaction and Functional Coupling Rules in Configuration Design, *Proceedings of ASME Design Engineering Technical Conferences*, DETC97/DTM-3869, Sacramento, CA, USA.

Kohlhase, N. and Birkhofer, H. (1996) Development of modular structures: the prerequisite for successful modular products, *Journal of Engineering Design*, Vol. 7, No. 3, pp. 279-91.

Kolter, P. (1989) From mass marketing to mass customization, *Planning Review*, Vol. 17, pp. 10-13.

Kotha, S. (1994) Mass Customization: The New Frontier in Business Competition, *Academy of Management Review*, Vol. 19, No. 3, pp. 588-592.

Kumar, K. R. and Sudharshan, D. (1988) Defensive Marketing Strategies: An Equilibrium Analysis Based on Decoupled Response Function Models, *Management Science*, Vol. 34, No. 7, pp. 805-815.

- Kusiak, A. and Chun-Che Huang (1996) Development of modular products, *IEEE Transactions on Components, Packaging, and Manufacturing Technology*, Part A, Vol. 19, No. 4, pp. 523-38.
- Kusiak, A. and Chow, W. S. (1987) Efficient Solving of the Group Technology Problem, *Journal of Manufacturing Systems*, Vol. 6, No. 2, pp. 117-124.
- Lau, R. S. (1995) Mass Customization: The Next Industrial Revolution, *Industrial Management*, Vol. 37, No. 5, pp. 18-19.
- Lu, S.C-Y., Tchong, D. (1990) Building Layered Models to Support Engineering Decision Making: A Machine Learning Approach, *Journal of Engineering for Industry*, ASME Transactions, Vol. 113, No. 1, pp. 1-9.
- Martin, M. V. and K. Ishii (1996) Design for Variety: A Methodology for Understanding the Costs of Product Proliferation, *Proceedings of the 1997 ASME Design Engineering Technical Conferences*, DTM-1610, Irvine, CA.
- Martin, M. V. and K. Ishii (1997) Design for Variety: Development of Complexity Indices and Design Charts, *Proceedings of 1997 ASME Design Engineering Technical Conferences*, DFM-4359, Sacramento, CA.
- Meyer, Marc H. and James M. Utterback (1993) The Product Family and The Dynamics of Core Capability, *Sloan Management Review*, Vol. 34, No. 3, pp. 29-47.
- Newcomb, P. J., Bras, B. and Rosen, D. W. (1997) Implications of Modularity on Product Design for the Life Cycle, *Proceedings of ASME Design Engineering Technical Conferences*, DETC96/DTM-1516, Irvine, CA, USA.
- Pahl, G. and Beitz, W. (1996) *Engineering Design: a Systematic Approach*, Springer, London.
- Pimpler, T. U. and Eppinger, S. D. (1994) Integration Analysis of Product Decompositions, *Proceedings of ASME Design Theory and Methodology Conference*, DE-Vol. 68, pp. 343-351.
- Pine II, B. J. (1993) *Mass Customization: The New Frontier in Business Competition*, Harvard Business School Press, Boston.
- Prasad, B. (1996) *Concurrent Engineering Fundamentals*, Prentice Hall, N.J..
- Roberts, E. B. and M. H. Meyer (1991) Product Strategy and Corporate Success, *IEEE Engineering Management Review*, Vol. 19, No. 1, pp. 4-18.
- Saaty, Thomas L. (1991) *The analytic hierarchy process*, McGraw-Hill, New York.
- Sanderson, S.W. (1991) Cost models for evaluating virtual design strategies in multicycle product families, *Journal of Engineering and Technology Management*, Vol. 8, No. 3-4, pp. 339-58.
- Sanderson, S. (1995) Managing Product Families: The Case of the Sony Walkman, *Research Policy*, Vol. 24, No. 5, pp. 761-782.
- Shiba, S., Graham, A., Walden, D. (1993) *A New American TQM*, Productivity Press, Portland, Oregon.
- Shocker, A. S. and Srinivasan, V. (1979) Multiattribute Approaches for Product Concept Evaluation and Creation: A Critical Review, *Journal of Marketing Research*, Vol. 16, No. 2, pp. 159-180.
- Steward, D. V. (1981) *Systems Analysis and Management: Structure, Strategy and Design*, Petrocelli Books, New York.
- Subrahmanian, E., A. Westerberg and G. Podnar (1991) Towards a Shared Computational Environment for Engineering Design, *Computer Aided Cooperative Product Development*, Springer Verlag.
- Suh, N. P. (1990) *The Principles of Design*, Oxford University Press, New York.
- Tseng, M. M. and Jiao, J. (1996) Design for mass customization, *Annals of the CIRP*, Vol. 45/1, pp. 153-156.
- Tseng, M. M. and Jiao, J. (1997a), A Variant Approach to Product Definition by Recognizing Functional Requirement Patterns, *Journal of Engineering Design*, Vol. 8, No. 4, pp. 329-340.
- Tseng, M. M. and Jiao, J. (1997b) A Pragmatic Approach to Product Costing: A Case Study in an Electronics Enterprise, *Advances in Industrial Engineering Applications and Practice II, Proceedings of the 2nd Annual International Conference on Industrial Engineering Applications and Practice*, J. J. G. Chen and A. Mital (eds.), pp. 1107-1112, San Diego, USA, November 1997.
- Thurston, D. L. (1990) Multiattribute Utility Analysis in Design Management, *IEEE Transactions on Engineering Management*, Vol. 37, No. 4, pp. 296-301.
- Ulrich, K. (1995) The role of product architecture in the manufacturing firm, *Research Policy*, Vol. 24, No. 3, pp. 419-440.
- Ulrich, K. T. and Eppinger, Steven D. (1995) *Product Design and Development*, McGraw-Hill, New York.
- Ulrich, K. and Tung, K. (1991) Fundamentals of Product Modularity, *Issues in Mechanical Design International 1991*, A. Sharon, Ed., New York, ASME, DE 39, pp. 73-79.

Ulrich, K.T. and Seering, W.P. (1990) Function Sharing in Mechanical Design, *Design Studies*, Vol. 11, pp. 223-234.

Yoshimura, M. and Takeuchi, A. (1994) Concurrent optimization of product design and manufacturing based on information of users' needs,

Concurrent Engineering: Research and Applications, Vol. 2, No.1, pp. 33-44.

Zimmermann, H.J. (1991) *Fuzzy Set Theory and its Applications*, Kluwer Academic Publishers, Boston.

Figure 1 Mass customization: Economic implications

Figure 2 The principle of PFA-based product development for mass customization

Figure 3 Structural implications and multiple views of a PFA

Figure 4 The and/or tree representation of the functional view of a product family

Figure 5 Design matrix decomposition for technical modularity

Figure 6 Representation of a building block class and its instances

Figure 7 Performance evaluation based on the utility of a product attribute

Figure 8 The C-U plot for building block evaluation (Modified from Ishii et al., 1995)

Figure 9 A graph representation of the configuration structure for a product family

Figure 10 Various types of power supply products

Table 1 An example of the FR hierarchy for power supplies

FR0: Universal low power AC/DC converters			
DESCRIPTIVE LEVEL	GENERIC LEVEL	TERMINOLOGY LEVEL	ENGINEERING LEVEL
FR1: Used in what country (Input Requirement)	FR11: Operating range	FR111: Line voltage	FR1111: Voltage range
		FR112: Input surge current	
		FR113: Line transient	
	FR12: Protection	FR121: Inrush current	FR1221: Brown-out FR1222: Drop-out
FR122: Power-line disturbance			
FR123: RFI/Surge suppression			
FR2: Used in what system (Output Requirement)	FR21: Power level	FR211: Total output power	
	FR22: Power quality	FR212: No. of output/Cross regulation	
		FR221: Regulation/Output voltage range	
		FR222: Overshoot (Turn on overshoot)	
		FR223: Output voltage	
		FR224: Ripple voltage	
		FR225: Output current	
		FR226: Holdup time	
	FR23: Loading	FR231: Dynamic loading	
		FR232: Isolated output	
		FR233: Feedback loop compensation	
	FR24: Protection	FR241: Over voltage protection (O/V)	
		FR242: Over current protection	
FR243: Short-circuit protection			
FR3: Used in what environment	FR31: Operating condition	FR311: Operating temperature (range)	
	FR32: Safety	FR312: Operating relative humidity	
		FR321: Safety approvals	
		FR322: EMI/EMC	
		FR323: Safety ground leakage current	
FR33: Mechanical requirement	FR331: Mechanical outline(Overall dimensions)		
	FR332: Connection/Connector/Electrical pin-out		
FR4: Used for what application	FR41: Reliability	FR411: MTBF hours (Continuous operation)	
	FR42: Quality	FR412: On/Off cycles (Repetitive operation)	
		FR421: Max. failure rate (percent)	
		FR43: Efficiency

Figure 11 Representation of the functional view of a PFA for power supply products

a) The push-pull regulator topology

b) The full-bridge regulator topology

Figure 12 Two different topologies for power supply design

Table 2 An example of the DP hierarchy for power supplies

First Level	Second Level	Third Level	Fourth Level	Fifth Level
DP0: Topology	DP1: Power section	DP11: Transformer	DP111: Core magnetic	DP1111: Core material
				DP1112: Core style
		DP12: Power switch	DP112: Winding	DP1113: Core size
				DP1121: # of turns
				DP1122: Wire gauge
	DP2: Control section	DP13: Output rectifier	DP121: Types of semiconductors	
			DP122: Ratings of semiconductors	
			DP123: Drive circuit	
		DP14: Output filtering	DP131: Diode technology	
			DP132: Ratings of rectifiers	
	DP3: Ancillary section	DP15: Input rectifiers	DP141: Output capacitors	
			DP142: Physical layout	
		DP21: Controller (IC)	DP151: Input rectifiers	
		DP22: Drive circuit	DP221: Zener shunt regulator	
			DP222: Large IC bypass capacitor	
	DP23: Housekeeping circuit		DP231: Output feedback circuit scheme	
			DP232: Error amplifier	
			DP233: Optoisolator	
			DP234: Resistor divider	
	DP32: Input filtering		DP311: Protection scheme	
			DP312: Protection circuit	
			DP321: Bulk input capacitor	
			DP322: Thermistor	

Initial Design Matrix			Clustered Design Matrix		
DPs		123221111321111231231112 331231215231421221314321 21222111113122212241113 1 2 3 1 2	DPs		11111331111111222332222 111115223143222122113333 111221122211123 21211234 12312 2
FRs	ID	000000000111111111122222 123456789012345678901234	FRs	ID	001110110122012201010011 682589071312743446302519
224	1	000000000000101000001100	331	4	011110000000000000000000
226	2	001000000000000000001000	1111	5	111110000000000000000000
412	3	00000000000010000000011	321	26	110110000000000000000000
331	4	000000010001001001000000	211	18	101110000000000000000000
1111	5	000001010001001001000000	223	27	111110000000000000000000
1221	6	000000001100000000000000	43	30	111010000001000000000000
1222	7	000000001100000001000000	1221	6	000001100000000000000000
112	8	000100000000000010000000	1222	7	000001110000000000000000
322	9	100000000000100000001000	121	20	001000110000000000000000
233	10	010010000010000001000000	123	29	000001010000000000000000
242	11	001000000000000000001000	224	1	000100000111000000000000
241	12	0010000000000000000001000	322	9	000000001110000000000000
232	13	010000000010000000100000	225	16	000000001111000000000000
231	14	010010000000000000100000	221	17	000000001101000000000000
243	15	001000000000000000001000	412	3	000000000000011100000000
225	16	100000000000100000001100	411	25	000000000000111000000000
221	17	100000000000100000000100	112	8	000000000000000001100000
211	18	000001000001001001000000	113	19	000000000000000001100000
113	19	000100000000000010000000	222	21	000000000000000001100000
121	20	000000000010000001000000	332	28	000000000000000000100000
222	21	000100000000000100000000	226	2	000000000000000000011000
212	22	010010000010000000100000	242	11	000000000000000000011000
421	23	001000000000000000010000	241	12	000000000000000000011000
323	24	001000000000000000010000	243	15	000000000000000000011000
411	25	000000100000010000000010	421	23	000000000000000000011000
321	26	000001010000001001000000	323	24	000000000000000000011000
223	27	000001010000100100100000	233	10	000000000000000000001110
332	28	001000000000000000000000	232	13	000000000000000000000101
123	29	000000001000000010000000	231	14	000000000000000000000110
43	30	000001010001000001000100	212	22	000000000000000000000111

Figure 13 Design matrix decomposition for technical modularity

Table 3 Power supply design modules

Transformer Module	
FRs	FR211, FR43, FR321, FR331, FR1111, FR223
DPs	DP1113, DP1112, DP1121, DP1122
Output Rectifiers & Filters Module	
FRs	FR123, FR121, FR1221, FR1222
DPs	DP151, DP321, DP322
Startup Module	
FRs	FR43, FR221, FR224, FR225, FR322
DPs	DP131, DP132, DP141, DP142
Power Switch & Controller Module	
FRs	FR411, FR412
DPs	DP121, DP122, DP123, DP21
Protection Module	
FRs	FR243, FR242, FR241, FR421, FR323, FR226, FR332
DPs	DP311, DP312
Voltage Feedback Module	
FRs	FR112, FR113, FR222
DPs	DP222, DP221
Input Module (Rectifiers & Filtering & RFI Filter/ Surge Suppression)	
FRs	FR212, FR231, FR232, FR233
DPs	DP233, DP231, DP232, DP234

Figure 14 An example of a modular structure for power supply design

Table 4 An example of building blocks in power supply design

FR-DP Mapping Relationship: $FRk = f_{FRk}(DPk1, DPk2)$			
Building Blocks Representation: $BBk = (FRk, DPk1, DPk2)$			
Building Blocks Variants	$FRk =$	$DPk =$ "Magnetic Core of Transformer"	
BBk	"Output Power (W)"	$DPk1 =$ "Core Type"	$DPk2 =$ "Core Size (mm)"
MPP-A	<5	MPP Toroid	16 (Diameter)
MPP-B	<25	MPP Toroid	20 (Diameter)
MPP-C	<50	MPP Toroid	30 (Diameter)
MPP-D	<100	MPP Toroid	38 (Diameter)
MPP-E	<250	MPP Toroid	51 (Diameter)
EEL-A	<5	E-E, E-L, etc. Core	11 (each side)
EEL-B	<25	E-E, E-L, etc. Core	30 (each side)
EEL-C	<50	E-E, E-L, etc. Core	30 (each side)
EEL-D	<100	E-E, E-L, etc. Core	47 (each side)
EEL-E	<250	E-E, E-L, etc. Core	60 (each side)

Figure 15 An example of economic evaluation of building blocks

Table 5 A tabular form of the configuration structure for a product family

ASSEMBLY LEVEL						DESCRIPTION	QUANTITY PER ASSY
1	2	3	4	5	6		
720184-001						NFN40-7608 (end product)	1
100020-400						DIODE FR 3A 400V MR854	1
160010						IC NVR -12V 1A 2% TO-220	1
210063-687						CAPACITOR AL 35V 680uF 20%	2
320040-240						RESISTOR CF 1/2W 5% 24 OHM	3
500441						HEATSINK NFN40	1
520069						INSULATOR MICA .715 X 1.0	1
520069-20						INSULATOR MICA W/O AMMO PACK	1
640019						THERMAL NON-SILICON HEATSINK	2
790184-001						SUB ASSEMBLY - NFN40-7608	1
130088						XSTR NCH MOSFET IRF830	1
150002-050						DIODE SCR 8A 50V	2
30020-332						RESISTOR CF 1/4W 5% 3.3K OHM	3
240019-103						CAPACITOR CER DISC 1KV .01uF	1
390012						THERMISTOR 3A 15% 10 OHM	1
444801						FUSE CER F H BREAK 3.15A 250V	1
510184						PCB - NFN40	1
800399						INDUCTOR -NFN40-7608	1
430036-17						WIRE MAG HVY #17 RED	2
820080						TOROID FER CTD .187X .375X .104	1
720184-004						NFN40-7610 (end product)	1
100049-045						DIODE SCH 16A 45V	1
160035						IC NVR -15V 1.5A 2% TO-220	1
210054-188						CAPACITOR AL 10V 1800uF 20%	2
320020-471						RESISTOR MO 1W 5% 470 OHM	4
500441						HEATSINK NFN40	1
520069						INSULATOR MICA .715 X 1.0	1
520069-20						INSULATOR MICA W/O AMMO PACK	1
640019						THERMAL NON-SILICON HEATSINK	2
790184-004						SUB ASSEMBLY - NFN40-7610	1
130088						XSTR NCH MOSFET IRF830	1
150005-020						DIODE ZNR 1W 20V 5% 1N4937	2
380002-501						RESISTOR VAR TADJ ST 500 OHM	3
220011-224						CAPACITOR MPST 63V .22uF 5%	1
390012						THERMISTOR 3A 15% 10 OHM	1
444801						FUSE CER F H BREAK 3.15A 250V	1
510184						PCB - NFN40	1
800398						INDUCTOR -NFN40-7610	1
430036-26						WIRE MAG HVY #26 RED	2
820080						TOROID PWDR-IR T68-52 AL=40	1
M-800398						MFG INST-800398	1
43009-750						TUBE HEATSINK 3" BLK	1

* Bolded part-codes represent building blocks.