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DESIGN FOR MASS CUSTOMIZATION BY DEVELOPING PRODUCT FAMILY ARCHITECTURE

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ABSTRACT

Mass customization is becoming an important agenda in industry and academia alike. This paper deals with mass customization from a product development perspective. A framework of design for mass customization (DFMC) by developing product family architecture (PFA) is presented. To deal with tradeoffs between diversity of customer requirements and reusability of design and process capabilities, DFMC advocates shifting product development from designing individual products to designing product families. As the core of DFMC, the concept of PFA is developed to assist different functional departments within a manufacturing enterprise to work together cohesively. A PFA describes variety and product families and performs as a generic product platform for product differentiation in which individual customer requirements can be satisfied through systematic decisions of developing product variants. Based on such a PFA, the DFMC framework provides a unifying integration platform for synchronizing market positioning, soliciting customer requirements, increasing reusability, and enhancing manufacturing scale of economy across the entire product realization process.

1. INTRODUCTION

Mass customization aims at meeting diverse customer needs while maintaining near mass production efficiency through economy of scope (Pine, 1993). Figure 1 (Tseng and Jiao, 1996) illustrates how mass production has an advantage in high volume production where the actual volume can defray the cost of huge investments in equipment, tooling, engineering, and training. However, satisfying each individual customer needs often can be translated into higher value, whereas lower production volume cannot justify the large investments. Because mass customization allows companies to garner the scale economy through utilizing repetitions, it is capable of reducing costs and lead time. Hence, mass customization can achieve 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.

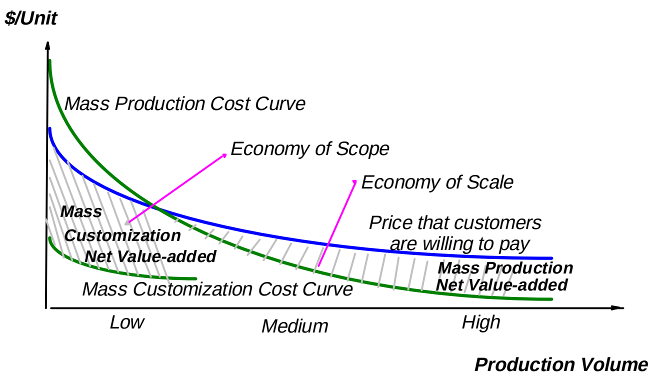

Figure1. The Economic Implications of Mass Customization

1.1 Literature Review

A sizeable body of literature on mass customization is emerging and involves many, if not most, aspects and issues of manufacturing enterprises and tackles mass customization from various perspectives such as in the fields of business strategy, marketing, manufacturing technology, customer engineering, and information technology, to name but a few.

A review of the existing approaches regarding mass customization suggests several major streams. One area where mass customization has prevailed as a hot topic in recent years is strategic management. In this context, much research has focused on contrasting mass production with mass customization approaches to competitive strategy (*e.g.,* Pine, 1993; Kotler, 1989). Some research work has been carried out towards mass customization by highlighting organizational mechanisms that foster knowledge (*e.g.,* Kotha, 1995). Meyer *et al.* (1993) anchor mass customization to the viewpoint of technology management and point out the correlation of a firm's product strategy to its underlying core capabilities. Hart (1995) defines and discusses mass customization in the context of the service industry. Some contributions relate mass customization to marketing (*e.g.,* Kotler, 1989). The organizational issues of mass customization have been briefed by Lau (1995), for example.

From an implementation viewpoint, a large number of research emphasizes the importance of information technology as an instrument for mass customization (*e.g.,* Moad, 1995). Quite a lot of literature sets the standpoint on manufacturing management (*e.g.,* Beaty, 1996) and advanced automation technologies (*e.g.,* Moad, 1995). Lee and Bilington (1994) advocate research on mass customization from a supply chain management perspective. Similarly, Hart (1996) tackles the logistic issues related to mass customization.

Moreover, mass customization research overlaps and intertwines with many other topics encompassing customer driven engineering and manufacturing (*e.g.,* Muntslag, 1994), lean production, flexibility, agile manufacturing, and one-of-a-kind production (*e.g.,* IFIP, 1992).

In terms of product development and engineering design, approaches to and strategies for variety design and product families and mass customizing goods are prevalent in the literature. Most of the work in strategic management and marketing research seeks to categorize or map the evolution and development of product families (*e.g.,* Wheelwright and Clark, 1992). Meyer *et al.* (1997) emphasizes the importance of establishing product platforms for product strategy and corporate success. In other work, Wheelwright and Clark (1992) suggest designing "platform projects"; Rothwell and Gardiner (1988) advocate "robust designs" as a means to generate a series of different products within a single product family; and Ulrich (1995) investigates the role of product architecture and its impact on product development. Collier (1981) stresses commonality across products within a product family as an effective means to cater to product variety. Chen *et al.* (1994) suggest designing flexible products which can be readily adapted in response to large changes in customer requirements by changing a small number of components or modules. Uzumeri and Sanderson (1995) emphasize flexibility and standardization as a means for enhancing product flexibility and offering a wide variety of products.

Martin and Ishii (1996; 1997) advocate design for variety by developing cost indices of providing variety. While their efforts actually aims at reducing technical variety, the strategy for functional variety, which should be encouraged, has not been explicitly distinguished from that for technical variety. In addition, Ishii *et al.* (1995) introduce the variety importance-cost map to help minimize the life-cycle cost associated with offering product variety. While their formulation of customer importance captures the relative importance of different product features (*i.e.,* weightings of evaluation criteria), it is difficult to reflect the "value" of a functional feature itself (performance evaluation of a feature against certain criteria).

The work of Fujita and Ishii (1997) tackles the fundamental issues regarding product variety design, including design specification analysis, system structure synthesis, configuration, and model instantiation. Simpson *et al.* (1996a; 1996b) try to design robust product families that are readily adaptable to the changing design requirements. They adopt statistical model building techniques and goal programming to formulate formal algorithms for designing product families. Stadzisz and Henrioud (1995) cluster products based on geometric similarities to obtain product families in order to decrease product variability within a product family in order to minimize the required flexibility of the associated assembly system. The challenge associated with the computational approaches to product variety design lies in that they rely on detailed design information and thus are more suitable for parameteric design instead of the early stages of design.

In summary, mass customization raises many implications for theory development and testing across a broad horizon. Although the notion of pursuing a customization strategy has great appeal, the current efforts towards mass customization either highlight the benefits while neglecting the means (Kotha, 1994, 1995), or deal with the requirements of mass customization in fragment. As a result, mass customization has drawn the criticism that it has the look and feel of a revolutionary paradigm but lacks of a coherent framework and thus remains a repackaging of pre-existing ideas with only limited synthesis (Kotha, 1994; 1995). Moreover, competitive strategies in the 1990s include diverse and related themes such as manufacturing flexibility, time-based competition, lean production, re-engineering, and continuous improvement. The structure and infrastructure issues are critical to the successful implementation of mass customization so as to be compatible with various strategies and technologies (Lau, 1995). Therefore, it is imperative to develop a coherent framework within which systematic approaches can be taken to enable the realization of mass customization.

1.2 Technical Challenges of Mass Customization

To understand mass customization, the requirements and technical challenges are first analyzed. The essence of mass customization lies in the product and service developers' being able to perceive and capture latent market niches and subsequently to develop technical capabilities to meet the diverse needs of target customers. Therefore, the requirements of mass customization reside with 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*.

Accordingly, the 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. In order to achieve such a balance, three major technical challenges are identified as follows (Tseng and Jiao, 1996; Jiao, 1998).

Reusability. Capturing repetitions in design and manufacturing to maximize reusability so as to achieve low costs and high efficiency, *i.e.*, the economy of scale, an advantage characterized by mass production.

Product platform. Providing a technical basis for accommodating customization, managing varieties, and leveraging core capabilities to optimize flexibility and foster a customer-focused and product-driven business.

Integrated Product Life-Cycle. Facilitating the context-coherent integration throughout the product development process and over the product life-cycle to achieve quick responsiveness.

2. DESIGN FOR MASS CUSTOMIZATION

In view of the above challenges, this research investigates mass customization from a product development perspective, namely design for mass customization (DFMC), based on the belief that mass customization can be effectively approached from design. Essentially, the attempt is to include customers into the product development life-cycle through proactively connecting customer needs to the capabilities of a company. The main emphasis of DFMC is to elevate the current practice of designing individual products to designing product families. In addition, DFMC advocates extending the traditional boundaries of product design to encompass a larger scope spanning from sales and marketing to distribution and services. Figure 2 summarizes the conceptual implications of DFMC in terms of the expansion of the context from both a design scope perspective and a product differentiation perspective.

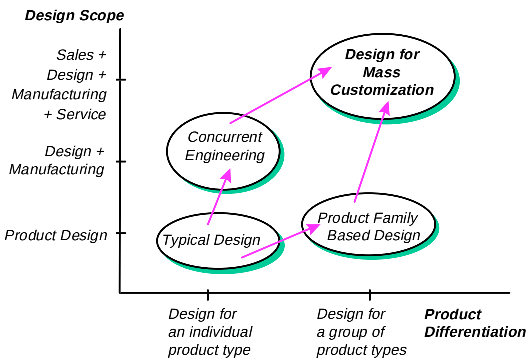

Figure 2. The Virtue of DFMC

To support customized product differentiation, a product family platform is required to characterize customer needs and subsequently to fulfill these needs by configuring and modifying well-established building blocks. Therefore, there are two basic concepts underpinning DFMC, namely the product family architecture (PFA) and subsequently the PFA-based product development life-cycle (PFA-PDLC), *i.e.*, family-based design. Figure 3 outlines such a framework of DFMC. Key issues regarding the PFA methodology include PFA fundamentals and PFA development. The PFA-PDLC resembles DFMC as a type of configuration design, thus involving issues such as design evaluation, product costing, and requirement management in product definition.

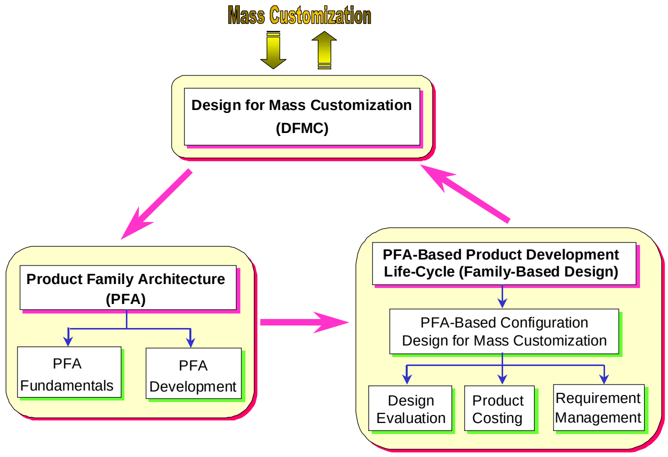

Figure 3. A Framework of DFMC

3. PRODUCT FAMILY ARCHITECTURE

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 reusability, 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 customer needs within a coherent framework.

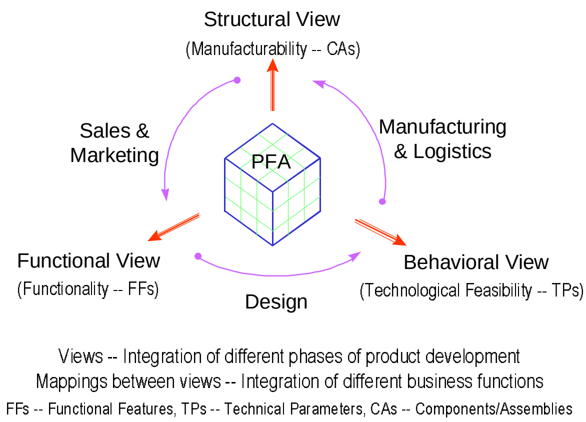

Figure 4. A FBS-View Representation of PFA

3.1 Representation of a PFA

In this research, based on the chromosome model (Andreasen, 1992) and design domains (Suh, 1990), a functional-behavioral-structural-view (FBS-view) product model and associated design mappings are established and employed as the basis of representing a PFA (Figure 4).

Functional View. The functional modeling for a single product has been widely investigated, *e.g.*, structural analysis and function structuring. The functional structure of a product consists of the functional elements (Ulrich, 1995), or the so-called functional features (FFs), and their interrelationships that involve 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 that embodies the customer 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 (a) different customer groups, (b) the FFs and their relative importance/priority for every customer group, and (c) the classification of FF instances for customers within each customer group.

Behavioral View. Corresponding to each customer group identified in the functional view, the behavioral 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 an electronic product design. In the behavioral view, modules and modular structures are defined in terms of technical parameters (TPs) corresponding to specific FFs 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 structural view of the PFA. Issues regarding the technical modeling of a technological solution (product technology) include (a) documenting TPs and the mappings from FFs to TPs, (b) determining technical modules by minimizing design coupling, (Suh, 1990; Johannesson, 1997), and (c) establishing modular structures for configuration design.

Structural View. The structural view is similar to Eren *et al.*'s physical model (1997). This structural 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 impose constraints on this realization to guarantee easy manufacturing and assembly operations without compromising the cost and lot-size constraints in order to keep the economy of scale. More specifically, the physical model consists of various types of components and assemblies (CAs) in order to realize technological solutions/product technologies generated in the behavioral view. Apart from mapping relationships of FF-TP-CA, an important concern associated with the structural view is the economic evaluation of granularity tradeoffs among various CAs options according to available process capabilities of a firm. This is approached by identifying suitable component clusters, or chunks as Pimmler and Eppinger (1994) called them, and assembly levels across all the products (families) incorporating volume and cost concerns.

3.2 Mappings Between the Views of a PFA

While corresponding to and supporting different phases of product development using a FBS-view product model, the PFA integrates several business functions in a context-coherent framework. This is embodied in the mappings between the three views of a PFA (Figure 4). Various types of customer needs (customer groups) are mapped from the functional view to the behavioral view characterized by solution principles (TPs and modular structures). Such a mapping manifests design activities. The mapping between the behavioral view and the structural view reflects considerations of manufacturing and logistics, where the modular structure and technical modules in terms of TPs are realized by the physical modules in terms of CAs through incorporating assessments of available process capabilities and the economy of scale. The sales and marketing functions involve the mapping between the structural view and the functional view, where the correspondence of a physical structure to its functionality provides necessary information to assist in negotiation among the customers, marketers, and engineers, *e.g.* facilitating the request-for-quotation (RFQ).

Table 1. An Example of Applying Class-Member Relationships to Characterize the Derivation of Varieties

VARIETY CLASS (FF VARIABLES)		VARIETY MEMBERS (FF INSTANCES)		
Customer Group 1 Specification of product family 1		Customers within Group 1 Individual specifications for product variants of Family 1		
$\{FFs\}_1$	FF1 = Total power	$\{FFs^*\}_1$	<200W	>200W & <1000W
	FF2 = Power Factor Correction		No	Yes
Customer Group 2 Specification of product family 2		Customers within Group 2 Individual specifications for product variants of Family 2		
$\{FFs\}_2$	FF1 = Total power	$\{FFs^*\}_2$	<100W	>100W & <500W
	FF2 = Number of outputs		Single	Dual
	FF3 = Safety		VDE, CSA	UL, VDE

3.3 Class-Member Relationships Underlying Variety

A PFA organizes and represents a variety of objects in different views using class-member relationships. For each type of object corresponding to a particular view, *i.e.*, functional, technical or physical modules, the variety of the object results from two layers. First the objects differentiate in terms of their attribute variables (*e.g.*, FFs, TPs, or CAs). Different sets of variables distinguish diverse types of objects. Then, for each type of objects (class) defined by a specific set of variables (class attributes), varieties can further result from diverse instances (members) of particular variables. That is, every variable may take on several values. Such a representation using class-member relationships reveals the sources and propagation of varieties involved in the three views of the PFA. Table 1 gives an application example of class-member relationships to variety characterization only in the functional view, where a variety class (noted as type I variety) is represented by its attribute variables, {FFs}, and a variety of members (noted as type II variety) within this class is characterized by different values (instances) of specific variables, {FFs*}.

Table 2. Modularity and Commonality for Characterizing Reusability in PFA

ISSUES	MODULARITY	COMMONALITY
Child-Parent Relationship	A-part-of	A-kind-of
Analysis Method	Decomposition	Clustering
Characteristic of Measure	Interaction	Similarity
Focused Objects	Type (Class)	Instances (Members)
Product Differentiation	Product Structure	Product Variants
Integration/Relation	Class-Member Relationship	

3.4 Modularity and Commonality

There are basically two issues inherent in reusability, namely the modularity and commonality. Table 2 highlights different implications of modularity and commonality regarding reusability, as well as the relation between them.

The concepts of modules and modularity are central in constructing an architecture (Ulrich, 1995). 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 that can be treated as logical units (Newcomb *et al.*, 1996). Therefore, *decomposition* is a major concern in modularity analysis. In addition, to capture and represent product structures across the entire product development process, the PFA achieves its modularity from multiple viewpoints, including functionality, solution technologies, and physical structures. Correspondingly, there are three types of modularity involved in the PFA, *i.e.*, functional modularity, technical modularity, and physical modularity.

What is important in characterizing modularity is the *interaction* between modules. Modules are identified in such a way that between-module (inter-module) interactions are minimized whereas within-module (infra-module) interactions may be high (Ulrich, 1995). Therefore, three types of modularity in the PFA are characterized by specific measures of interaction for particular views. As for functional modularity, the interaction is exhibited by the relevance of FFs across different customer groups. Each customer group is characterized by a particular set of FFs. Customer grouping lies only in the functional view and is independent of the other two views, that is, it should be solution-neutral. In the behavioral view, modularity is determined according to technological feasibility of design solutions. The interaction is thus judged by the coupling of TPs to satisfy given FFs (referred to as design coupling) regardless of their physical realization in manufacturing. In the structural view, physical interactions derived from manufacturability become the major concern of the physical modularity.

It is commonality that reveals the difference of the architecture of product families from that of a single product. While modularity resembles decomposition of product structures and is applicable to describing module (product) types, commonality characterizes the grouping of *similar* module (product) variants under specific module (product) types characterized by modularity. Corresponding to the three types of modularity, there are three types of commonality in three PFA views. Functional commonality manifests itself through functional classification. That is, it clusters similar customer requirements into one class. Similarity is measured by the distance between FF instances (FF*s). In the behavioral view, each technical module, characterized by a set of TPs corresponding to a set of FFs, exhibits commonality through clustering similar TP instances (TP*s) by chunks. Instead of measuring similarity in CA instances (CA*s), physical instances (instances of CAs for a physical module type) are grouped according to appropriate categorization of engineering costs derived from assessing existing capabilities and estimated volume, *i.e.*, economic evaluation.

The relation between modularity and commonality is embodied in the class-member relationships. A product structure is defined in terms of its modularity where module types are specified. Product variants derived from this product structure share the same module types and take on different instances of every module type. In other words, a class of products (product family) is described by modularity and product variants differentiate according to the commonality between module instances.

3.5 PFA Composition

A PFA aims at supporting DFMC in the way of configuration design, and accordingly, a PFA consists of four major elements, *i.e.*, the *product line taxonomy*, *building blocks*, *configuration rules*, and *economic evaluation* (Jiao, 1998). Meeting diverse customer requirements and achieving volume economy simultaneously can thus be achieved by systematic planning of functional diversity and reusability in terms of building blocks and their configuration structures across the functional, behavioral and structural views.

4. PFA DEVELOPMENT

Essentially, PFA development resides with the appropriate formulation of building blocks with the synergetic consideration of the functional, behavioral and structural perspectives. A building block has a two-fold meaning, *i.e.*, modularity and commonality. First, the type of a building block is determined through modularity which means to decompose a system into modules. Then for a particular module (building block type), there exist various instances that exhibit certain similarity (Such a similarity of instances is often referred to as commonality as observed in many group technology applications). Several variants can thus be derived by clustering similar module instances. These variants become the final form of building blocks. Therefore, building blocks are formulated through two layers, the modularity layer for module types first and then the commonality layer for variants. The relation of these two layers is embodied in class-member relationships. An overview of PFA development, involving two layers and across three views, is given in Table 3.

Table 3. An Overview of PFA Development

ISSUES OF PFA	FUNCTIONAL VIEW	BEHAVIORAL VIEW	STRUCTURAL VIEW	PRODUCT FAMILIES
(1) Modularity	Functional Modularity	Technical Modularity	Physical Modularity	Product Structure
Modules	Functional Modules	Technical Modules	Physical Modules	
Module Variables	$M_{Fi} = \{FFs, Ws\}$	$M_{Tj} \subset \{TPs\}$	$M_{Pk} = \{CAs\}$	
Interaction Measure	FFs Relevance	Design Coupling	Physical Interaction	
Modular Structure	N/A	Topological Structure	Configuration Structure (BOM)	
Module Identification (Decomposition)	- Pareto Analysis - Qualitative Classification	- Design Matrix Decomposition (DMD)	- Interaction Matrix Analysis (IMA) - Modular Function Deployment (MFD)	
Concerns	- Customer Segmentation - Functionality	- Technological Feasibility (Product Technology)	- Manufacturability - Process Capabilities	
(2) Commonality	Functional Commonality	Technical Commonality	Physical Commonality	Product Variants
Instances	FFs Values of Customer Needs	TPs Values of Technical Modules	CAs Values of Physical Modules	
	$M^*_{Fi} = \{FFs^* \mid \forall FF \in M_{Fi}\}$	$M^*_{Tj} = \{TPs^* \mid \forall TP \in M_{Tj}\}$	$M^*_{Pk} = \{CAs^* \mid \forall CA \in M_{Pk}\}$	
Similarity Measure	$d_{q,q+1} = \sqrt{\sum_{p=1}^{n} \left(w_p \left(\frac{FF^*_{p,q} - FF^*_{p,q+1}}{FF^*_p} \right)^2 \right)}$, $\forall FF_{p,q} \in M_{Fi}$	$d_{q,q+1} = \sqrt{\sum_{p=1}^{n} \left(w_p \left(\frac{TP^*_{p,q} - TP^*_{p,q+1}}{TP^*_p} \right)^2 \right)}$, $\forall TP_{p,q} \in M_{Tj}$	$U_{ij} = \frac{1}{\pi} \tan^{-1}\{\alpha(DoS_{ij} + \beta)\} + 0.5$ $DoS_{ij} = \lambda \frac{FR^*_{ij} - FR^T_{ij}}{FR^*_{ij}}$ $U_i = \prod^{n} (U_{ij})^{w_{ij}}$	
Clustering Analysis	Fuzzy C-Means Clustering Analysis (FCM)		Economic Evaluation (U-C Plot)	
Variants	$\{M^V_{Fi}\}$	$\{M^V_{Tj}\}$	$\{M^V_{Pk}\}$	
(3) Integrateability	FF-TP Mapping - Design Matrix - Solution Generation	TP-CA Mapping - Manufacturability - Instantiation of Technical Modules based on Existing Capabilities		Integration

4.1 Functional View — Customer Requirement Analysis

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. Figure 5 illustrates the steps for systematic analysis of customer requirements with formal techniques.

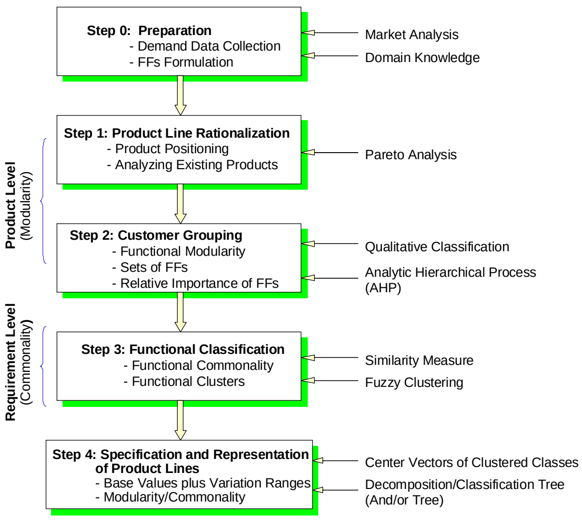

Figure 5. The Flowchart of Customer Requirement Analysis in the Functional View of a PFA

Step 0: Preparation. *(1) Inductive FFs formulation based on existing products.* The FFs formulation lies in the customer and functional domains of a design process (Suh, 1990) and aims at developing a FF hierarchy which consists of FF variables and their interrelationships with respect to the 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). *(2) Deductive FFs formulation based on product strategies.* Based on the FF hierarchy formulated above, the functional specifications of existing products can be mapped into various FF instances to represent specific products.

Step 1: Product line rationalization. The purpose of positioning existing products is to identify the company's strength by systematic analysis and consolidation of product lines to align them with available capabilities and long-term goals of a company. Anderson (1997) suggest positioning criteria and applying Pareto analysis to the positioning of existing products.

Step 2: Customer grouping. By customer grouping, it refers to formulating different sets of FF variables for various customer groups. That is, the functional modularity in a PFA is embodied in various customer groups characterized by specific sets of FFs. That is, $M_{Fi} \sim CG_i \sim \{(FF_{ij}, w_{ij}) \mid j = 1, 2, ..., n_i\}$, where CG_i denotes a particular customer group (*i*), M_{Fi} represents this customer group as a functional module from a PFA perspective, w_{ij} denotes the relative importance of the *j*th FF of CG_i, and n_i is the total number of FFs in CG_i. Since customer profiles have been projected and instantiated by a population of FF instances, a Pareto analysis can be employed to extract key FFs for characterizing different customer groups. In addition, qualitative classification dependent upon domain knowledge is often required. Moreover, the analytic hierarchical process (AHP; Satty, 1991) can be applied to explicating the relative importance of these FFs.

Step 3: Functional classification for each customer group. Within each customer group represented by a particular set of FF variables, even though all the customers share the same set of FFs, various functional varieties could result from different desired values for a particular FF variable (different FF instances). The classification of various FF instances for a particular set of FF variables is referred to as *functional classification*. The focus of functional classification is the commonality analysis through clustering similar FF instances into clusters and representing these FF instances by the base values and variation ranges of the center vectors of clustered classes. In our research, the fuzzy C-means (FCM) cluster analysis technique (Zimmermann, 1991) is adopted. As a measure of the similarity of customer needs (*i.e.*, FF instances), the distance among the desired values for product attributes (*i.e.*, FFs) is 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 $(\forall j = 1, 2, ..., m)$ desired value $FF^*_{i,j}$ and customer $j+1$'s desired value $FF^*_{i,j+1}$ is defined for this customer group (product family) with product attribute *i* $(\forall i = 1, 2, ..., n)$ as follows:

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

where $\overline{FF^*_i} = \frac{\sum_{j=1}^{m} FF^*_{i,j}}{m}$ 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. All the weights are derived from the AHP in the customer grouping.

Step 4: Specification and representation of product lines. Through functional classification, similar customers in terms of their desired-values for a FF variable comprise a cluster that is characterized by a representative center vector. Usually, several clusters are formed and thus necessitate a product family design, where each product variant aims at each cluster of customers. In planning product family design, the target value for a FF variable and its variation range can be determined based on domain knowledge as a result of understanding the characteristics of the clustered class obtained from functional classification. Usually, various desired FF values of customers in the same cluster are averaged to obtain a base FF value which is subsequently used as the target FF value for a planned product variant. The variation range of a base value is usually determined according to the variance of FF instances within a cluster of customers. Since mostly more than one FF variable is involved, a base FF value and its variation range 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 FFs.

In order to describe both a family and its product variants in a single formalism, a combined decomposition/classification tree (and/or tree) is adopted to represent the product lines in the functional view of a PFA from an abstract level to individual instances (Jiao, 1998).

4.2 Behavioral View — Modularization of Technological Solutions

The major concern in the behavioral view is to explore the modularity underlying various available technologies applied to existing products in meeting given customer groups. For a particular customer group identified in the functional view, the following procedures are suggested for modularizing technological solutions (product technologies) associated with product family design for the customer group (Figure 6).

Step 0: Preparation. *(1) TPs formulation.* Given the generic FFs formulated in the functional view and solution technologies applied in existing products, TPs are identified based on their relevance to fulfilling FFs. All the TPs and their interrelationships are represented by a TP hierarchy. *(2) Documenting FF-TP mapping relationships.* Based on the understanding of solution principles, the mapping relationships from FFs to TPs are extracted and documented in the form of a design matrix. A particular 0/1 element indicates whether or not a correspondence between a FF and a TP exists.

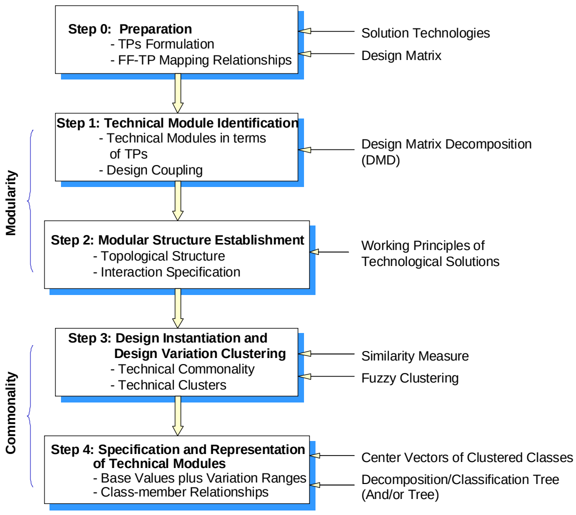

Figure 6. The Flowchart of the Modularization of Technological Solutions in the Behavioral View of a PFA

Step 1: Technical module identification. Given a design matrix with 0-1 elements denoting the corresponding FF-TP relationships, matrix decomposition techniques (Pimmler and Eppinger, 1994) can be applied to inducing element cells, each of which indicates what-how relationships between a set of FFs and a set of TPs. Based on the design matrix formulated above, the design matrix is decomposed into chunks for technical modules. The algorithm developed by Kusiak and Wang (1992) is adopted in design matrix decomposition.

Step 2: Modular structure establishment. Once technical modules in terms of TPs have been identified according to the technological feasibility, the modular structure needs to be established to describe technical modules and their interrelationships. A modular structure in the behavioral view is usually called a *topological structure* in that it reveals the overall schematic of arranging technical modules for synthesizing a solution. In establishing a modular structure, the working principle of a solution is of particular concern in determining how to fit technical modules to the solution. Interactions are specified according to the inter-cell elements in the decomposed design matrix.

Step 3: Design instantiation and design variation clustering. According to the design matrix, a feature vector space is defined for a particular technical module, M_{Tk}, identified above as the following:

$$\mathbf{X}^{k,m'+n'} = (\mathbf{FF}^k, \mathbf{TP}^k) = (FF_1^k, FF_2^k, ..., FF_{m'}^k, TP_1^k, TP_2^k, ..., TP_{n'}^k). \quad (2)$$

Instances of this technical module can thus be obtained based on existing products by instantiating the above vector. That is, $\{\mathbf{X}_j^{k*}\} \sim \{(\mathbf{FF}_j^{k*}, \mathbf{TP}_j^{k*}) \mid j = 1, 2, ..., v\}$, where $\mathbf{FF}^k = (FF_1^k, FF_2^k, ..., FF_{m'}^k)$ and $\mathbf{TP}^k = (TP_1^k, TP_2^k, ..., TP_n^k)$ are defined for M_{Tk}.

The similarity of design instances for a particular technical module is measured by the distance between design instances in terms of the feature vector space of this module, *i.e.*, Eq. (2). Suppose there are v design instances that are characterized by Eq. (2). The distance $d_{j,j+1}$ between instance j $(\forall j = 1,2,...,v)$ and instance $j+1$ is defined as follows:

$$d_{j,j+1} = \sqrt{\sum_{i=1}^{m}\left(w_i^{FF}\left(\frac{FF_{i,j}^{k*} - FF_{i,j+1}^{k*}}{\overline{FF_i^{k*}}}\right)^2\right) + \sum_{i=1}^{n}\left(w_i^{TP}\left(\frac{TP_{i,j}^{k*} - TP_{i,j+1}^{k*}}{\overline{TP_i^{k*}}}\right)^2\right)}, \quad (3)$$

where $\overline{FF_i^{k*}} = \frac{\sum_{j=1}^{v} FF_{i,j}^{k*}}{v}$ and $\overline{TP_i^{k*}} = \frac{\sum_{j=1}^{v} TP_{i,j}^{k*}}{v}$ are used to evaluate FF and TP values having different units on the same scale, w_i^{FF} and w_i^{TP} are the weighting coefficients specified for FFs ~ $\{FF_l^k \mid l = 1,2,...,m'\}$ and TPs~$\{TP_l^k \mid l = 1,2,...,n'\}$, respectively. All weights are determined according to the AHP. Based on the above similarity measure, the FCM cluster analysis is conducted so as to identify clusters of design instances.

Step 4: Specification and representation of technical modules. Similar to the specification of functional classes, the variants (M_T^V) of a technical module (M_T) are determined according to the understanding of clustered classes of instances, $\{M_T^*\}$, of this technical module. The base value and its variation range is specified for each variant of a technical module according to the center vector and variance for each cluster. That is, $M_{Ti}^V \sim (\overline{\mathbf{X}_i^*}, \Delta\mathbf{X}_i^*) \sim (\overline{\mathbf{FF}_i^*}, \overline{\mathbf{TP}_i^*}, \Delta\mathbf{FF}_i^*, \Delta\mathbf{TP}_i^*)$. The representation of a technical module (building block in terms of TPs) involves both its functional and structural aspects. A FF-TP tuple is thus appropriate to capture the correspondence between a technical module and its intended function. In addition, a class-member relationship is applicable to characterize the differentiation of technical building blocks resulting from either the type (class) of a FF-TP mapping or different instances (members) of a particular mapping.

4.3 Structural View — Economic Evaluation of Physical Modules

In the structural view, the technical modularity is realized in terms of physical product structures. Components and sub-assemblies (CAs) are determined for technical modules identified in the behavioral view. Manufacturing concerns, such as manufacturability, costs, volume, and schedule, are taken into account in such a transformation (*i.e.*, instantiation) from 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 modularity analysis (Figure 7).

Step 0: Preparation. *Determining physical instances of technical modules based on available process capabilities.* For each technical module identified in the behavioral view, its corresponding components and assembly structures can be determined according to the assessment of available process capabilities and with reference to existing products.

Step 1: Physical module identification. What is important in physical modularity is the physical interactions between CAs. An interaction matrix is first formed in terms of pairwise analysis of between-CAs interactions. Then the interaction matrix analysis (IMA) technique presented by Pimmer and Eppinger (1994) is applied to identify candidate physical modules (chunks of CAs).

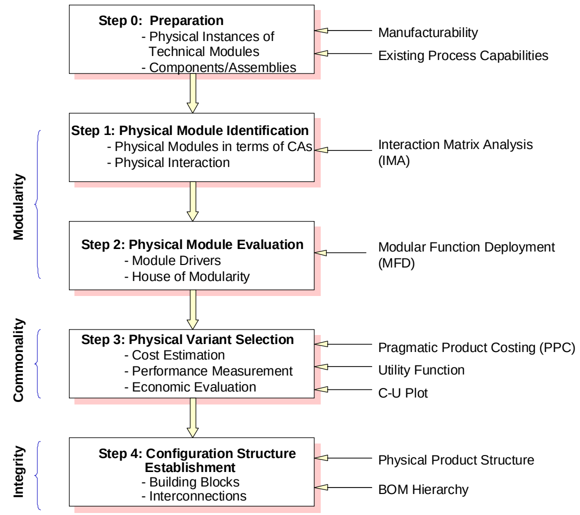

Figure 7. The Flowchart of the Economic Evaluation of Physical Modules in the Structural View of a PFA

Step 2: Physical module evaluation. All the possible physical modules are evaluated against several module drivers so as to select appropriate physical modules. The modular function deployment (MFD) method (Erixon, 1996) is used in such an evaluation.

Step 3: Physical variant selection. The determination of physical variants involves mostly the economical evaluation. Appropriate physical variants are selected according to their contributions in maintaining the economy of scale and providing “functional variety”. In other words, the “common denominators” should be maximized only for those building blocks that are both utility-important to the customers and cost-effective. *(1) Cost estimation of physical modules.* In this research, we adopt a pragmatic approach to cost estimation based on standard time estimation (see Section 5.2). *(2) Performance measurement of physical modules.* The performance of a physical module is determined by calculating its relative utility with respect to its intended functions, *i.e.*, the FFs, propagated from the functional view through FF-TP and TP-CA mappings. In this research, a utility function from Yoshimura and Takeuchi (1994) is adopted to convert diverse FF scales to a common scale. The utility U_{ij} of a module i for its functional attribute j (characterized by FF_{ij}) responses to the value of DoS_{ij} (degree of satisfaction), expressing the distance (*i.e.*, discrepancy) of the module’s performance value FF_{ij}^* away from its target value FF_{ij}^T determined in the functional view of PFA. When the performance of a module 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 (Yoshimura and Takeuchi, 1994) is as follows:

$$U_{ij} = \frac{1}{\pi}\tan^{-1}\{\alpha(DoS_{ij} + \beta)\} + 0.5, \quad (4)$$

where $DoS_{ij} = \lambda \frac{FF_{ij}^* - FF_{ij}^T}{FF_{ij}^*}$, α and β are coefficients obtained by the regression analysis of existing products, $\lambda = 1$ if the functional attribute, FF_{ij}, is more preferable when the value of DoS_{ij} increases (*i.e.*, the-more-the-better), and $\lambda = -1$ if the functional attribute FF_{ij} is more preferable when the value of DoS_{ij} decreases (*i.e.*, 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 $U_i = \prod_{j=1}^{n}(U_{ij})^{w_{ij}}$, where *n* is the total number of functional attributes for determining the performance (U_i) of module *i*, thus $\forall j = 1,2,...,n$. *(3) Economic evaluation of physical modules.* The evaluations against technical and economic criteria presented above lead to a pair-wise overall ratings for physical building blocks. For illustrative simplicity, here we present a pragmatic tool, C-U plot, modified from Ishii's I-C plot (Ishii *et al.*, 1995). For a more rigorous solution of this multi-criteria design evaluation problem, we have developed a fuzzy ranking approach using an information-content measure (see Section 5.1). 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, called a C-U plot, can be used (Jiao, 1998).

Step 4: Configuration structure establishment. With various physical modules identified for each product family (customer group), 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 along different levels of assembly. 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.

5. PFA-BASED PRODUCT DEVELOPMENT LIFE-CYCLE

Issues associated with PFA-PDLC involves design evaluation, product costing, and requirement management for product definition, as described next.

5.1 Configuration Design Evaluation

Under the umbrella of a PFA, mass customization product development is resembled as a kind of configuration design, where a class of products can widely variegate the selection and assembly of pre-defined building blocks at different levels of abstraction to satisfy diverse customization requirements. The importance of concept evaluation is apparent because a poor selection of either a building block or a configuration structure can rarely be compensated at later design stages and can give rise to a great expense of redesign costs (Pahl and Beitz, 1996). Resulting from its paramount importance in configuration design, this alternative (concept) evaluation and selection problem has received enormous attention (Finger and Dixon, 1989). Though a number of methods have been investigated, there is still much to be desired due to the hindrances inherent in the evaluation and selection process. Difficulties associated with this task lie in the following aspects (Jiao, 1998: *(1) Complexity of problem-solving:* Concept evaluation is characterized by multicriteria decision-making under uncertainty; *(2) Handling of various decision criteria:* While traditional criteria are labeled tangible and can be quantified by numerical variables, a host of other criteria may be labeled intangible that are characterized by qualitative measures and often involve linguistic terms; and *(3) Assessment of product performance:* The essence of mass customization resides with maximizing the overlap between a firm's capabilities and customer needs. The degree of customer satisfaction with a particular design alternative needs to be explicitly represented and measured with respect to its functionality. Aside from a large number of technical parameters, it is difficult to estimate product performance in terms of technical information involving various metrics.

While traditional mathematical programming and utility analysis enhance algorithm-rigorous optimization modeling, such methods require the expected performance with respect to each criterion to be represented with a quantitative form. They are not appropriate for use in the early design stage, where some qualitative design criteria, *i.e.*, intangible criteria, are involved and difficult to quantify (Thurston and Carnahan, 1992). Fuzzy analysis excels in capturing semantic uncertainty with linguistic terms, whereas it requires discreet deliberation in dealing with crisp information. That is, a domain-meaningful method is needed to fuzzify each tangible criterion whose evaluation is naturally estimated as an ordinary real variable (Carnahan *et al.*, 1994). Another challenge lies in the incomparability between various criteria (Wang, 1997), thus necessitating some mechanisms to be capable of converting various types of performance evaluation with respect to different criteria to a common metric so as to specify suitable membership functions for them.

To address the above issues, we develop a fuzzy ranking methodology for concept evaluation with emphasis on the assessment of product performances in the context of mass customization. The fuzzy preference relation (Nakamura, 1985) is applied to modeling the fuzziness on the level of a single criterion as well as on a global level. The ranking approach integrates linguistic terms and fuzzy numbers into the fuzzy preference model so as to characterize both intangible and tangible criteria. In addition, the information content (Suh, 1990) is employed to streamline diverse measures of design criteria into a common metric and connect customer satisfaction to the technical capabilities of a design. Moreover, the fuzzy line segment (Carnahan *et al.*, 1994) is employed to fuzzify the crisp measurements of tangible criteria in order to be compatible with the universe of discourse defined for the intangible criteria. Furthermore, the analytic hierarchy process (AHP; Saaty, 1981) is used for determining subjective customer preferences.

Fuzzy Ranking Methodology. Suppose $A=\{a_1, a_2, \ldots, a_m\}$ is a finite set of design concepts or alternatives, where each alternative is evaluated according to *n* criteria, noted as $C=\{c_1, c_2, \ldots, c_n\}$. The performance of alternative a_i with respect to criterion c_j is measured by a rating (referred to as the degree of satisfaction), noted as $DoS_j(a_i)$, $\forall a_i \in A, \forall c_j \in C$. The multicriteria evaluation of an alternative $a \in A$ is defined by a vector, $DoS(a)=[DoS_1(a), DoS_2(a), \ldots, DoS_n(a)]$, which is comprised of the performances of this alternative on the *n* criteria. Moreover, the relative importance (customer preference) of a criterion is expressed by a weighting factor, noted as w_j, $\forall c_j \in C$. These weights are linked by the usual normalization constraint: $\sum_{j=1}^{n} w_j = 1, \forall c_j \in C$. An alternative *a* is preferred to *b* if and only if there is sufficient evidence (referred to as the degree of dominance, noted as DoD) to believe that *a* is better than *b* (*i.e.*, *a* dominates *b*, noted as $a \succ b$) or at least *a* is as good as *b* (*i.e.*, *a* is indifferent from *b*, noted as *a* ~ *b*). The evidence for ranking decision-making is derived from fuzzy preference relations between alternatives (Zimmermann, 1987).

To rank fuzzy members, a Hamming distance-based approach proposed by Tseng and Klein (1989) is employed owning to its advantage in computational efficiency over other methods. The fuzzy multicriteria decision making procedures perform generally in three steps. *(1) Partial preference relations.* A partial preference relation $P_j'(a_i, a_k)$ indicates a monocriterion evaluation between two alternatives a_i and a_k ($\forall a_i, a_k \in A$, $i,k=1,\ldots,m$) for criterion $c_j \in C$. It is obtained by a pairwise comparison of their performance estimates, *i.e.*, $DoS_j(a_i)$ and $DoS_j(a_k)$, which are represented with fuzzy numbers. *(2) Aggregation of partial preference relations.* The aggregation phase defines the multicriteria preference relations $P''(a_i, a_k)$ between every pair of alternatives a_i and a_k ($\forall a_i, a_k \in A$, $i,k=1,\ldots,m$), taking into account the relative importance of different criteria. To compensate the partial preference relations for each criterion, an aggregation function is used, usually defined as following:

$$P''(a_i, a_k) = \sum_{j=1}^{n} (w_j P_j'(a_i, a_k)) = \sum_{j=1}^{n} (w_j P(DoS_j(a_i), DoS_j(a_k))) \quad (5)$$

where $\forall a_i, a_k \in A\ (i,k=1,\ldots,m)$ and w_j is the relative importance of criterion c_j. The aggregation function (Wang, 1997) modified from Tanino's aggregation rule (Tanino, 1984) is adopted for Eq. (5). *(3) Exploitation and ranking decision rule.* To derive ranking structure on the basis of scores, the degree of dominance (DoD) is defined as follows, indicating that an alternative a_i is simultaneously preferred to other alternatives in *A*:

$$DoD(a_i) = \sum_{\substack{a_k \in A \\ a_k \neq a_i}} P''(a_i, a_k). \quad (6)$$

Therefore, the decision rule for determining the complete ranking order of a set of alternatives can be defined as:

$\forall a_i, a_k \in A,\ i,k=1,\ldots,m$:

a_i is preferred to a_k: $a_i \succ a_k \Leftrightarrow DoD(a_i) > DoD(a_k)$

a_i is indifferent from a_k: $a_i \sim a_k \Leftrightarrow DoD(a_i) = DoD(a_k)$.

The complete order ranking structure can thus be derived based on this rule.

Criterion Performance Evaluation. The bottleneck of design evaluation lies in the quality of estimating the performances of alternatives with respect to every criteria. However, in the current literature, the performance estimates are mostly given by default. The engineering approaches to assessing criterion performances are considered implicitly, if not ignored. This section tackles this linchpin ingredient of design evaluation. *(1) Identification of decision criteria.* Notwithstanding that most literature assumes that decision criteria are given by default, in practice, the identification of criteria involves quite a complex product definition process. Consisting of various design requirements, the product specification provides a basis for formulating evaluation criteria. Through investigating the hindrances inherent in the product definition process, we advocated a variant approach to developing product specifications by recognizing functional requirement patterns from existing products (see Section 5.3). The functional requirement patterns can particularly facilitate identifying decision criteria for the purpose of design evaluation. *(2) Evaluation of intangible criteria.* In order to use linguistic variables for precise modeling of imprecise statements in assessing performances on intangible criteria, this research adopts a seven-level linguistic scale according to the approach of Chen *et al.* (1992). *(3) Evaluation of tangible criteria.* In view of the aforementioned challenges in assessing the performances of tangible criteria, this research advocates measuring the tangible criterion performance with information content (Suh, 1990). The performance evaluation of an alternative $a_i \in A$ with respect to a tangible criterion $c_j \in C^T$ can be defined by the information content measure as the following:

$$DoS_j^T(a_i) = \frac{1}{\log_2\left(\frac{L_j^{sr}(a_i)}{\Delta L_j(a_i)}\right)+1}, \quad (7)$$

where $L_j^{sr}(a_i)$ and $\Delta L_j(a_i)$ are the system range and common range, respectively, of the alternative a_i with respect to the tangible criterion c_j, $\forall a_i \in A$, $c_j \in C^T$, and a uniform distribution is assumed for the tangible criterion $c_j \in C^T$. Since the value of $DoS_j^T(a_i)$ ranges from 0 to 1, the fuzzy line segment method, proposed by Carnahan *et al.* (1994), can subsequently be adopted for the purpose of fuzzifying crisp measurements.

5.2 Pragmatic Product Costing

The major drawbacks of traditional approaches to product costing include lack of manufacturing knowledge, reliance on the detailed design description, poor cost function approximation, and inability to update estimation algorithms by using actual cost data (Ostward, 1992). A pragmatic approach to product costing prior to the actual production run is developed by adopting the activity-based costing (ABC) concept and is developed based on the estimated processing time (Tseng and Jiao, 1997b).

The approach involves two stages, namely the preparatory stage and the production stage (Figure 8). In the preparatory stage, standard routings are first extracted from existing products. A generic activity hierarchy is established according to the analysis of standard routings, where cost drivers for each activity are identified and summarized by appropriate cost-related design features (CDFs). Then the Maynard Operation Sequence Technique (MOST; Maynard, 1997) is employed to analyze each operation of standard routings to determine the associated standard-time. Historical cost data is analyzed to induce the relationships between the CDFs and standard-time, namely Time-Estimating Relationships (TERs). By allocating plant-wide overhead costs to standard routings, the unit price of standard-time is established to indicate Cost-Estimating Relationships (CERs). A library of material costs is also summarized from existing products. In the production stage, CDFs are first induced from the schematic of a new design. Then a "dummy process plan" for this design can be inferred and used to retrieve the associated TERs to determine its time estimate. Once a standard-time has been estimated, CERs can be applied to compile the total product cost by adding the estimated material costs.

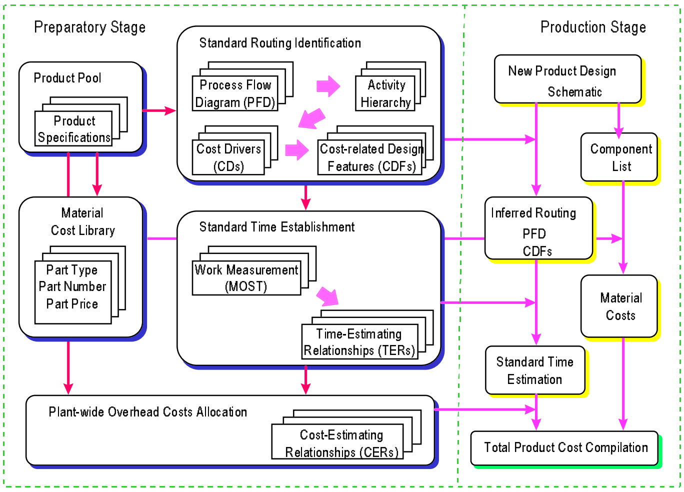

Figure 8. A Pragmatic Product Costing Approach

5.3 Requirement Management for Product Definition

Mass customization poses an increasing importance of customer recognition, thus exerting an impact on the product definition stage of design. Product definition is usually a tedious elaboration process enacted between the customers, marketers, and designers. The difficulties associated with product definition lie in the following aspects (Tseng and Jiao, 1997a): *(1) Contextual mismatching:* Usually, the customers, marketers, and designers employ different sets of contexts and perspectives to express the requirements; *(2) Lack of defined structures in requirements:* Variables and their interrelationship with requirements are often poorly understood and are usually expressed in abstract or conceptual terms, which leads to work on the basis of vague assumptions; *(3) No structured mapping:* The relationships between customer needs, functional requirements, and design parameters are often not clearly available in an early stage of design; and *(4) Life cycle customer requirements:* The whole spectrum of customer requirements over the product life cycle needs to be addressed. Customers include anyone downstream of the design team in the product realization process, along with the end users.

To improve product definition, a variant approach to requirement management by recognizing functional requirement patterns (noted as PDFR) is developed in this research (Tseng and Jiao, 1997a). Figure 9 gives an outline of the PDFR methodology which consists of the recognition and the adoption phases. In the recognition phase, FR patterns are recognized from existing product designs in terms of a FR topology, FR classifications, and FR templates. Apparently, the functional view of a PFA provides conducive guidelines for recognizing functional requirement patterns, embodying the mindset of capturing customer needs according to the technical capabilities. In the adoption phase, FR patterns are applied to domain requirement information management. Figure 10 shows an product definition activity model based on the PDFR methodology and its relevance to improving customer needs elicitation, generating product specifications, and managing this information in product definition.

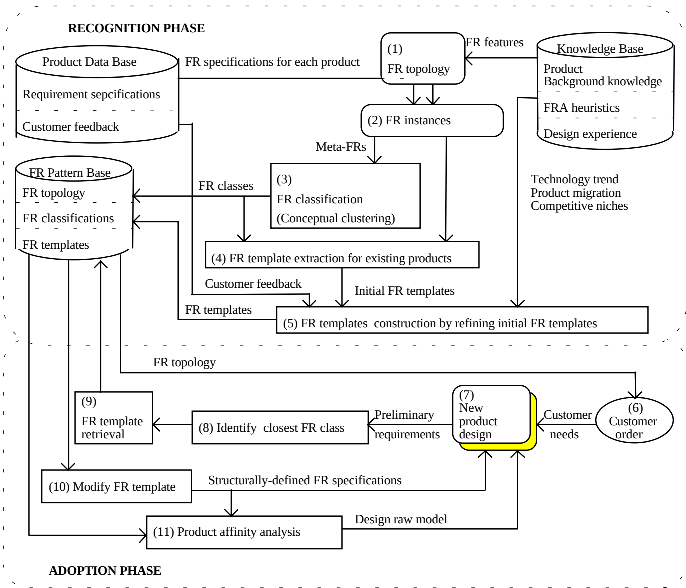

Figure 9. A Two-Phase Methodology for Product Definition

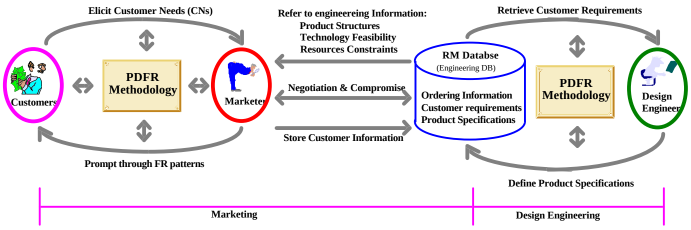

Figure 10. A Product Definition Activity Model Based on the PDFR methodology

6. CASE STUDIES FOR POWER SUPPLY DESIGN

This section reports case studies conducted in a local electronics company for power supply products (Jiao, 1998).

Table 4. An Example of the FR Hierarchy for Power Supplies

FR0: Universal low power AC/DC power supplies

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	
		FR122: Power-line disturbance	FR1221: Brown-out
			FR1222: Drop-out
		FR123: RFI/Surge suppression	

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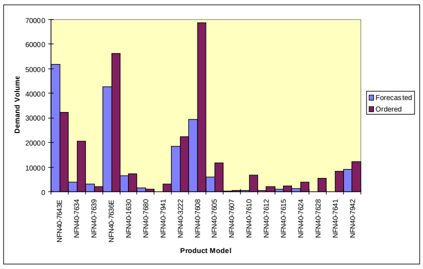


Figure 11. An Example of Product Volume Statistics

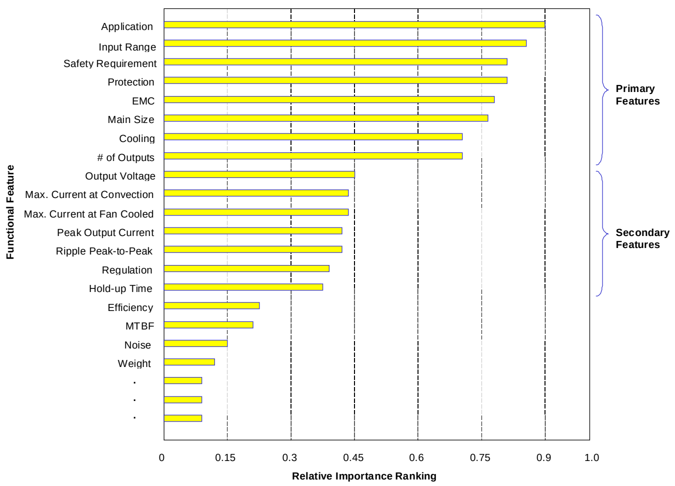


Figure 12. An Example of Identifying Key FFs using Pareto Sort

First of all, customer requirement analysis is conducted to develop the functional view of PFA. General FFs regarding power supply design are identified and formulated in a hierarchical form through comprehensive interviews with domain experts. For illustrative simplicity, here we give only FF formulations for the low power AC/DC converters (Table 4). Based on sales data, demand volumes for every product are analyzed to position existing product offerings. Figure 11 shows an example of product volume statistics. To identify key FFs for characterizing specific customer groups, all general FFs are evaluated for their relative importance with respect to different customer groups. Figure 12 presents an example of exploring customer preference by weighting the associated FFs based on the AHP. A Pareto sort helps identify critical FFs as key FFs. Thus, product families can be distinguished and characterized by these key FFs.

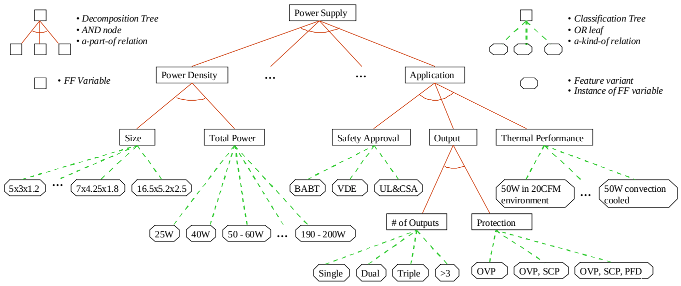


Figure 13. Representation of the Functional View of a PFA for Power Supply Products

According to above formulated FFs, more than 300 existing product models belonging to the customer group of low power AC/DC converters are instantiated into various FF instances. Since these FF instances vary widely due to diverse desired values and/or ranges for specific FFs, the functional classification procedure is applied to group similar customer specifications into one cluster and to determine the base values and their variation ranges for each cluster of functional specifications. Figure 13 presents the results of functional classification, in which various base values and variation ranges for each FF variable are determined based on the experts' knowledge as a result of understanding the characteristics of the clustered classes. In practice, the functional view of a PFA is usually embodied in a coding system. Such a coding system emphasizes the functional similarity among various products. Its focus is on the product level and thus is different from a coding system at the part level as widely used in group technology applications.

Table 5. An Example of the DP Hierarchy for Power Supplies

1st Level	2nd Level	3rd Level	4th Level	5th Level
DP0: Topology	DP1: Power section	DP11: Transformer	DP111: Core magnetic	DP1111: Core material
				DP1112: Core style
			DP112: Winding	DP1121: # of turns
				DP1122: Wire gauge
		DP12: Power switch	DP121: Types of semiconductors	
			DP122: Ratings of semiconductors	
			DP123: Drive circuit	

** This table is truncated due to page limitations.*

Existing technologies for power supply design are then investigated for the behavioral view of PFA. According to functional specifications and considering technological trends and existing process capabilities, one of the many topologies, the fly-back topology, is selected as the solution technology, which is very suitable for low power AC/DC converters. Once the solution technology has been determined, the TPs are then formulated with respect to the FFs. Table 5 shows the results of TPs formulation. The FF-TP mapping relationships are documented in the left half of Figure 14. Following the matrix decomposition procedures adopted in the PFA methodology, the design matrix is decomposed into cells (right half of Figure 14), from which technical modules are induced. Figure 15 shows a higher level modular structure revealing the working principle of design and highlighting the arrangement of different technical modules (building blocks in terms of TPs) for configuration design. More specifically, it determines the way in which the power holding parts of a power supply are configured. An example (transformer module) of clustering design variation for technical commonality is given in Figure 16. Table 6 shows several design variants of the transformer module based on the understanding of clustered classes in Figure 16.

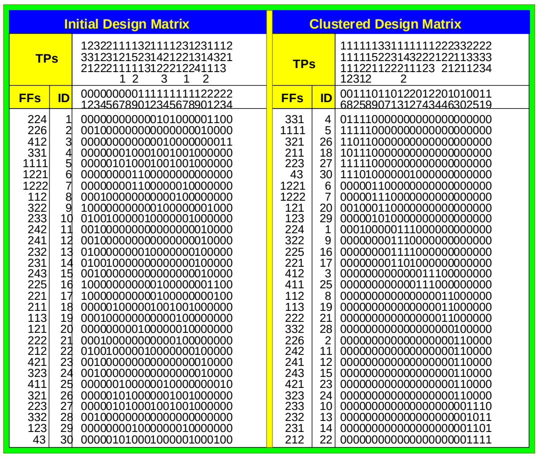


Figure 14. Design Matrix Decomposition for Technical Modularity in Power Supply Design

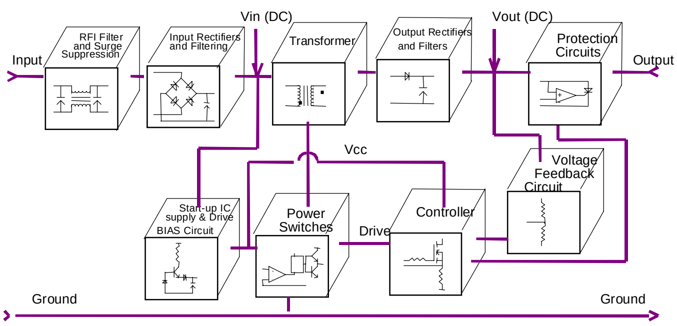
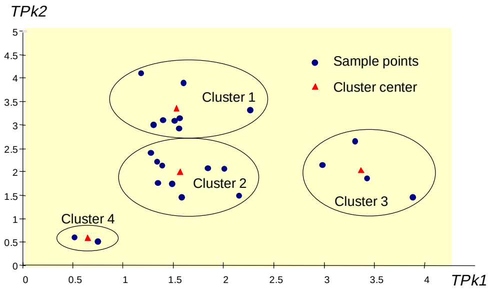


Figure 15. An example of a Topological Structure for Power Supply Design in the Behavioral View of PFA



$$P_{out} = \frac{W_a A_c B_{max} f}{0.68 d_w} = \frac{1}{0.68}\left(\frac{W_a A_c}{d_w}\right)(B_{max} f), \text{ where}$$

P_{out} Total output power of the supply (W)
B_{max} Peak operating flux density (G)
f Frequency of operation (Hz)
d_w Area of the wire used in the primary winding in m^2
W_aA_c Size of the one-winding inductor (m^4)

$$FFk = f_k(TPk2, TPk1) = f_k(TPk), \text{ where}$$
$FFk = P_{out}$
$TPk =$ Magnetic core
$TPk1 = B_{max} f$ Core type
$TPk2 = \frac{W_a A_c}{d_w}$ Core size

Figure 16. An Example (Transformer Module) of Design Instances Clustering in a Feature Vector Space

Table 6. Results of Clustering Design Variation for Figure 16

FF-TP Mapping Relationship: $FFk = f_k(TPk1; TPk2)$			
Building Blocks Variants BB^V_k	Building Blocks Representation: $BBk = \{FFk; TPk1, TPk2\}$		
	FFk = "Output Power (W)"	TPk = "Magnetic Core of Transformer"	
		$TPk1$="Core Type"	$TPk2$="Core Size (mm)"
MPP-A	<50	MPP Toroid	16 - 30 (Diameter)
MPP-B	<100	MPP Toroid	38 - 51 (Diameter)
EEL-C	<50	E-E, E-L, *etc.* Core	11 - 30 (each side)
EEL-D	<100	E-E, E-L, *etc.* Core	47 - 60 (each side)

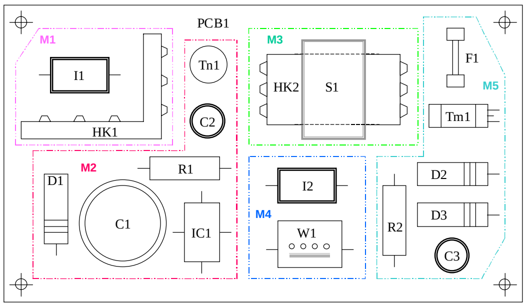


Figure 17. An Example of PCB Layout for Switching Power Supply Products

For each technical module identified in the behavioral view, the related TPs are instantiated as physical components and/or assemblies by considering available resources and existing process capabilities of the company. Figure 17 presents an example of a physical implementation of a particular power supply design. The associated CAs are listed in Table 7. These CAs are necessary in order to instantiate all technical modules of a power supply in terms of physical structures, such as the PCB only relevant to the structural view.

Physical modules are identified in terms of the physical interactions between CAs. In the physical design of a power supply, the printed-circuit board (PCB) layout has to be determined where various CAs are routed to achieve physical performance. In the physical routing of a PCB, the spatial interactions are of paramount importance compared with energy, information and material types of interactions (Pimmler and

Eppinger, 1994). Considerations involved in interaction analysis include the neighborhood of CAs, the EMI/EMC effect, the length of path, the component size, the assembly sequences, and so on. Figure 18 shows an example of the result of interaction matrix analysis for a power supply. Possible physical modules obtained from Figure 18 are correspondingly shown in Figure 17. According to Figure 18, there are four modules that can be obviously determined, *i.e.*, M1 ~ {I1, HK1}, M2 ~ {D1, C1, Tn1, C2, R1, IC1}, M3 ~ {I2, W1}, and M4 ~ {S1, HK2}. However, R2, F1, Tm1, D2, D3, and C3 can either be grouped into one module or treated separately. A MFD evaluation is thus conducted to make such a decision, from which an output module, M5 ~ { R2, F1, Tm1, D2, D3, C3}, is suggested.

Table 7. An Example of CAs for the Physical Structure of Power Supply Products Corresponding to Figure 17

PART NO.	DESCRIPTION	PART NO.	DESCRIPTION
I1	Surge Suppression Inductor	IC1	Controller IC
I2	Transformer Core	C1	Input Filtering Capacitor
HK1	Heat-sink for Surge Suppression	C2	Startup Driver Capacitor
		C3	Output Filtering Capacitor
HK2	Heat-sink	R1	Startup Driver Resistor
D1	Input Rectification Diode	R2	Voltage Feedback Resistor
D2	Protection Diode	W1	Transformer Wiring
D3	Output Rectification Diode	F1	Protection Fuse
S1	Power Switcher	PCB1	Printed-Circuit Board
Tn1	Startup Driver Transistor	Tm1	Protection Thermistor

COMPONENT		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
I1	A	+2	+2	+1	+1	0	-1	-1	-2	0	0	0	0	0	0	-2	-2	-2	-2	0
HK1	B	+2	+2	+1	+1	+1	0	0	0	+1	+1	0	-2	0	0	0	0	0	0	0
D1	C	+1	+1	+2	+2	+2	+2	+2	+2	-2	-2	-2	-1	0	0	-1	-1	-1	-1	0
C1	D	+1	+1	+2	+2	+2	+2	+2	+2	-2	0	-2	-1	0	0	-1	-1	-1	-2	0
Tn1	E	0	+1	+2	+2	+2	+2	+2	+2	-1	-1	-1	-1	0	0	-1	-1	-1	-1	0
C2	F	-1	0	+2	+2	+2	+2	+2	+2	-1	0	-2	-2	0	0	0	-1	-1	-1	0
R1	G	-1	0	+2	+2	+2	+2	+2	+2	0	0	0	0	-1	-1	-1	-1	-1	-1	-1
IC1	H	-2	0	+2	+2	+2	+2	+2	+2	+1	+1	+1	+1	0	0	0	0	0	0	0
I2	I	0	+1	-2	-2	-1	-1	0	+1	+2	+2	+1	+1	0	0	-1	-1	-1	-1	0
W1	J	0	+1	-2	0	-1	0	0	+1	+2	+2	+1	+1	0	0	-1	-1	-1	-1	0
S1	K	0	0	-2	-2	-1	-2	0	+1	+1	+1	+2	+2	0	0	-1	-1	-1	-1	0
HK2	L	0	-2	-1	-1	-1	-2	0	+1	+1	+1	+2	+2	0	0	+1	+1	+1	+1	0
R2	M	0	0	0	0	0	0	-1	0	0	0	0	0	+2	+1	+1	+1	+1	+1	0
F1	N	0	0	0	0	0	0	-1	0	0	0	0	0	+1	+2	+1	0	0	0	0
Tm1	O	-2	0	-1	-1	-1	0	-1	0	-1	-1	-1	+1	+1	+1	+2	+1	+1	+1	0
D2	P	-2	0	-1	-1	-1	-1	-1	0	-1	-1	-1	+1	+1	0	+1	+2	+1	+1	0
D3	Q	-2	0	-1	-1	-1	-1	-1	0	-1	-1	-1	+1	+1	0	+1	+1	+2	0	0
C3	R	-2	0	-1	-2	-1	-1	-1	0	-1	-1	-1	+1	+1	0	+1	+1	0	+2	0
PCB1	S	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	+2

Figure 18. An Example of Interaction Matrix Analysis

Table 8. Examples of Various Transformer Variants

PART NO.	VARIANTS OF TRANSFORMER	PART NO	VARIANTS OF TRANSFORMER
800398	**EEL-B** (Output Power <25W)	**800396**	**EEL-C** (Output Power <50W)
430036-26	WIRE MAG HVY #26 RED	430036-26	WIRE MAG HVY #26 RED
820082	TOROID PWDR-IR T68-52 AL=40	820082	TOROID PWDR-IR T68-52 AL=40
MI-800398	MFG INST-800398	**800392**	**MPP-C**
43009-750	TUBE HEATSINK ¾" BLK	430014-018	TUBING TFE XLT WL #26 B-130
…	…	430036-24	WIRE MAG HVY #24 RED
800390	**MPP-B** (Output Power <25W)	820120-1001	CORE E-FER AL=272
430014-018	TUBING TFE XLT WL #26 B-130	**800393**	**MPP-D** (Output Power <100W)
430016-26	WIRE BUS BAR TINNED CU #20	430014-018	TUBING TFE XLT WL #26 B-130
820120-0000	CORE E-FER E32 UNGAPPED	430036-30	WIRE MAG HVY #30 RED
…	…	820120-0000	CORE E-FER E32 UNGAPPED

Various physical variants for a particular physical module are possible. Table 8 lists examples of transformer variants that vary in terms of their physical attributes (the type and size of the core and the wiring method) along with their expected performances (output power). Four types of target performance have been determined in the functional view, *i.e.*, 25W, 40W, 60W, and 100W. The performance of each transformer is evaluated against these targets according to the procedure introduced in Section 4.3. In our case, the utility function taking on the form of Eq. (4) 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 introduced in Section 5.2. Figure 19 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 19, 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 technical modules and thus yield various types of components and assemblies.

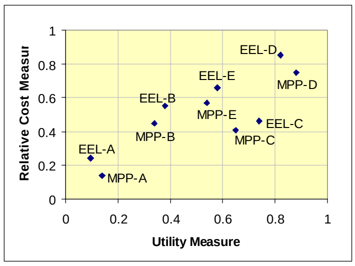


Figure 19. An Example of the Economic Evaluation of Building Blocks

Table 9. A Tabular Form of the Configuration Structure for a Product Family in the Structural View of PFA

ASSEMBLY LEVEL 1	2	3	4	5	6	7	DESCRIPTION	Quantity per Assembly
720184-001							NFN40-7608 (end product)	1
	100020-400						DIODE FR 3A 400V MR854	1
	…						…	
	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
		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
	…						…	
	100029-200X						DIODE FR 8A 200V BYW29-200	1
	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
		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
			MI-800398				MFG INST-800398	1
			43009-750				TUBE HEATSINK ¾" BLK	1

** BOLDED PART-CODES REPRESENT BUILDING BLOCKS*

With reference to the modular structures in the behavioral view, the configuration structure of product family design is established with respect to identified building blocks. Table 9 presents a part of a simplified configuration structure for a specific product family in which the configuration structure is given in a tabular form to circumvent tedious graph representation of family-level BOM. In practical production systems, a part coding system is usually used to represent different components and sub-assemblies for modules and/or end products. As illustrated in Table 9, different indented levels conform to the assembly levels from component to sub-assemblies and to end products. Various building blocks (those with their part codes bolded in Table 9) can be either a component or a sub-assembly and are shared at different levels across the entire product family. Finally, configuration design procedures are formulated according to the PFA in which various building blocks are well established in three consecutive views together with modular structures in each view.

Table 10. Specifications of the Design and System Ranges

Performance Evaluation		Tangible Criteria: Thermal Resistance (°C/W) c_1	Size: Length (mm) c_2	Size: Width (mm) c_3	Cost ($) c_4
System Range	a_1	4.8-38.6	13.4-30.1	8.4-18.6	1.7-1.9
	a_2	3.8-34.5	6.6-21.1	5.7-20.0	2.4-2.7
	a_3	4.6-40.1	12.5-30.4	8.6-19.2	1.6-2.0
	a_4	1.1-32.4	5.6-22.2	4.4-18.1	3.8-4.3
	a_5	2.9-35.7	7.8-25.4	5.6-16.8	3.5-4.1
Design Range		≤5.6	11.2-18.6	6.6-14.7	≤3.95
Common Range	a_1	4.8-5.6	13.4-18.6	8.4-14.7	1.7-1.9
	a_2	3.8-5.6	11.2-18.6	6.6-14.7	2.4-2.7
	a_3	4.6-5.6	12.5-18.6	8.6-14.7	1.6-2.0
	a_4	1.1-5.6	11.2-18.6	6.6-14.7	3.8-3.95
	a_5	2.9-5.6	11.2-18.6	6.6-14.7	3.5-3.95
Infor-mation Contents	a_1	5.40	1.68	0.70	0
	a_2	4.09	0.97	0.82	0
	a_3	5.15	1.55	0..80	0
	a_4	2.80	1.17	0.76	1.74
	a_5	3.60	1.25	0..47	0.42
$DoS_j^T(a_i)$	a_1	0.156	0.373	0.590	1.000
	a_2	0.196	0.507	0.549	1.000
	a_3	0.163	0.392	0.556	1.000
	a_4	0.263	0.462	0.569	0.365
	a_5	0.217	0.444	0.681	0.707

Performance Evaluation		Intangible Criteria: Mounting c_5	Compatibility c_6
$DoS_j^I(a_i)$	a_1	Poor	Good
	a_2	Medium Good	Medium
	a_3	Medium Poor	Medium Good
	a_4	Medium	Medium
	a_5	Very Good	Medium

As an example, the heat-sink selection is used to demonstrate the fuzzy ranking methodology for configuration design evaluation for mass customization. A heat-sink is a kind of component part in power supply design. Due to many vendors of heat-sink and diverse characteristics of thermal design, heat-sink design has always faced a serious problem that there exist too many varieties and thus too many options. One evident strategy towards mass customization is to reduce heat-sink varieties through a part standardization program. For instance, in the power supply company under our study, heat-sinks have been reduced from 20+ models to only 5. These new designs are supposed to be able to accommodate all the design requirements of power supply products offered by the company that originally necessitate 20+ heat-sinks. Under such a situation. the performance of new heat-sink designs needs to be evaluated.

Table 10 summarizes the general requirements of heat-sink design, involving both intangible and tangible criteria. For the five heat-sink alternatives, customer expectations and technical requirements are identified in terms of the design ranges of every design criteria (Table 10). For the intangible criteria, the performances of heat-sinks are specified using linguistic terms from the universe of discourse. The technical capabilities of different heat-sinks are characterized by the system ranges of every tangible criteria. The information content of each heat-sink design indicates its degree of satisfying given design specifications (Table 10). The information content measures are real numbers that represent the performance levels for all alternative designs. Using the approach in Section 5.1, we can convert these crisp measurements into fuzzy levels, once the *DoS* measures are obtained. According to a *DoS* measure, we can locate the adjacent fuzzy numbers in the universe of discourse and the distance from the smaller of them. Accordingly, the membership functions for these fuzzy line segments are derived. In such a way, the crisp performance levels are converted into fuzzy numbers that are consistent with the universe of discourse defined for the linguistic terms, hence integrating both intangible and tangible criteria into fuzzy analysis. The shapes of all the membership functions are shown in Figure 20. At this point, the fuzzy ranking procedure can be followed. Partial and aggregated fuzzy preference relations are derived for every pair of alternatives for each criterion. Then, the degree of dominance for each alternative is calculated according to Eq. (6). Finally, based on the ranking decision rule, the ranking order is derived, and thus the optimal design can be determined.

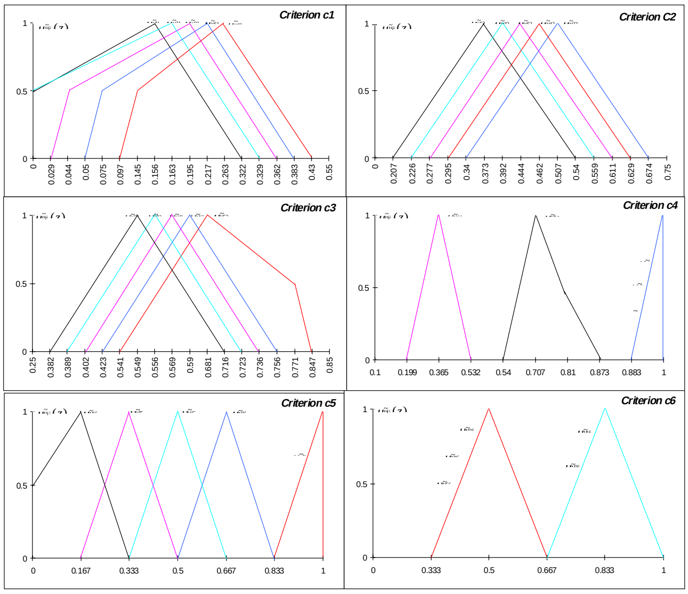


Figure 20. Membership Functions for the Performance Evaluations on Every Criteria

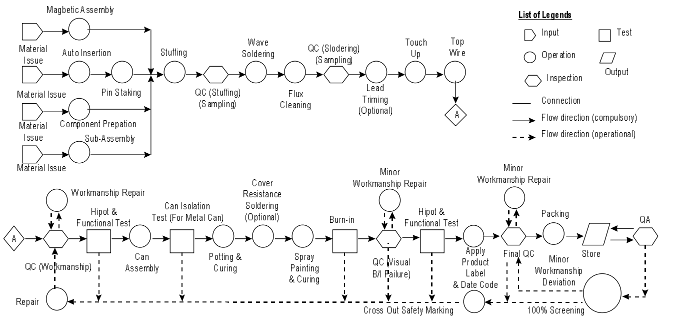


Figure 21. Process Flow Diagram (PFD) for the PCB Assembly of Encapsulated AC/DC Converters

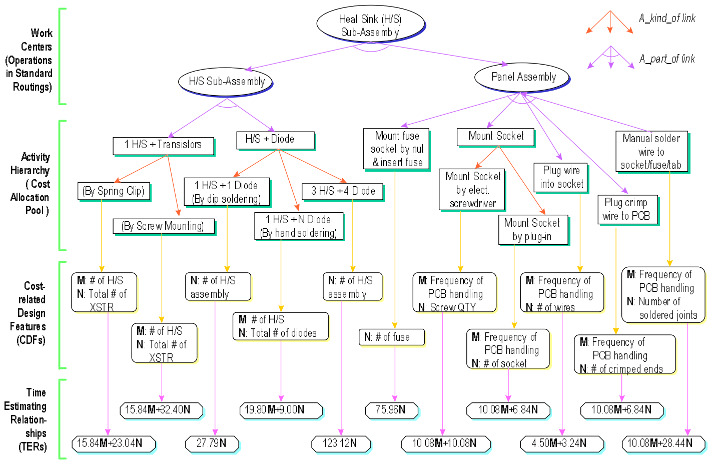
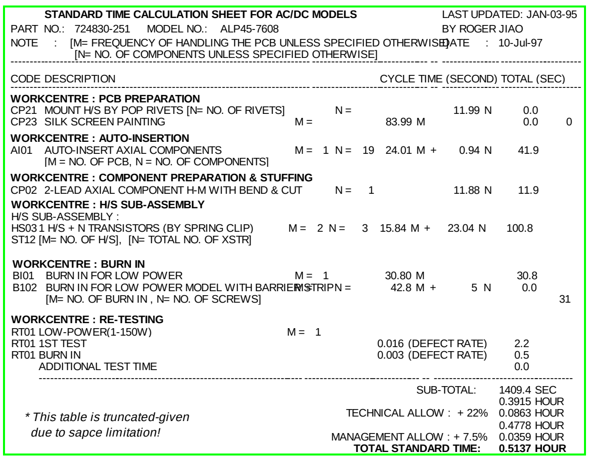


Figure 22. An Example of Costing Structure Design in PPC



STANDARD TIME CALCULATION SHEET FOR AC/DC MODELS — LAST UPDATED: JAN-03-95
PART NO.: 724830-251 MODEL NO.: ALP45-7608 — BY ROGER JIAO
NOTE : [M= FREQUENCY OF HANDLING THE PCB UNLESS SPECIFIED OTHERWISE] — DATE : 10-Jul-97
[N= NO. OF COMPONENTS UNLESS SPECIFIED OTHERWISE]

CODE	DESCRIPTION			CYCLE TIME (SECOND)		TOTAL (SEC)	
WORKCENTRE : PCB PREPARATION							
CP21	MOUNT H/S BY POP RIVETS [N= NO. OF RIVETS]		N =		11.99 N	0.0	
CP23	SILK SCREEN PAINTING	M =		83.99 M		0.0	0
WORKCENTRE : AUTO-INSERTION							
AI01	AUTO-INSERT AXIAL COMPONENTS [M = NO. OF PCB, N = NO. OF COMPONENTS]	M = 1	N = 19	24.01 M +	0.94 N	41.9	
WORKCENTRE : COMPONENT PREPARATION & STUFFING							
CP02	2-LEAD AXIAL COMPONENT H-M WITH BEND & CUT		N = 1		11.88 N	11.9	
WORKCENTRE : H/S SUB-ASSEMBLY							
	H/S SUB-ASSEMBLY :						
HS03	1 H/S + N TRANSISTORS (BY SPRING CLIP)	M = 2	N = 3	15.84 M +	23.04 N	100.8	
ST12	[M= NO. OF H/S], [N= TOTAL NO. OF XSTR]						
WORKCENTRE : BURN IN							
BI01	BURN IN FOR LOW POWER	M = 1		30.80 M		30.8	
B102	BURN IN FOR LOW POWER MODEL WITH BARRIER STRIP [M= NO. OF BURN IN , N= NO. OF SCREWS]	M =	N =	42.8 M +	5 N	0.0	31
WORKCENTRE : RE-TESTING							
RT01	LOW-POWER(1-150W)	M = 1					
RT01	1ST TEST			0.016 (DEFECT RATE)		2.2	
RT01	BURN IN			0.003 (DEFECT RATE)		0.5	
	ADDITIONAL TEST TIME					0.0	

SUB-TOTAL: 1409.4 SEC
0.3915 HOUR
TECHNICAL ALLOW : + 22% 0.0863 HOUR
0.4778 HOUR
MANAGEMENT ALLOW : + 7.5% 0.0359 HOUR
TOTAL STANDARD TIME: 0.5137 HOUR

** This table is truncated-given due to sapce limitation!*

Figure 23. An Example of Standard Time Calculation Sheet

The implementation of the pragmatic product costing (PPC) approach starts with the development of standard routings. Figure 21 gives an example of process flow diagram for the PCB assembly of encapsulated AC/DC converters. To establish the cost structure of ABC, each operation in a standard routing is treated as a cost center and is analyzed to determine the activities that fulfill this operation. All the activities for a cost center are organized by an activity hierarchy. Figure 22 shows the activity hierarchy for the operation of a heat sink sub-assembly, along with the identification of CDFs. Based on MOST, the standard time for each activity is established (Figure 23), along with the approximation of TERs (Figure 24). The derivation of CERs is based on the allocation of overhead costs at different levels of a company through calculating the consumption of TERs. The worksheet in Table 11 illustrates the procedure of total product cost compilation in the PPC approach.

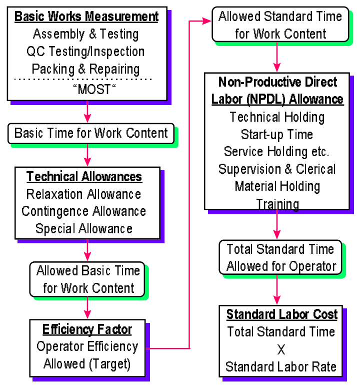


Figure 24. Standard-Time Establishment and TERs Approximation

Table 11. Product Costing Worksheet for PPC

Material Costing:	**ALP45-7608**
Component list: *{CPi, i=1, 2, ..., m}*	
where m = Total types of components	Schematic
Direct material cost ($): $C_M = \sum(CPi * UPi)$	
where UPi=Unit price of CPi	14.106
Material overhead rate (%): *MOH*	12.7%
Burdened material cost ($): $CC_M = C_M * (1 + MOH)$	15.8975
Standard-time Estimation:	
Activity hierarchy & TERs	CDFs
Total stand time (hour): *StdT*	0.5137
Direct Labor Costing:	
HK standard hour percent (%): δ	100%
ZS standard hour percent (%): $1-\delta$	0
HK standard labor rate ($/hour): *LR1*	4.750
ZS standard labor rate ($/hour): *LR2*	0.830
Direct labor cost - HK ($): $C_{DL1} = StdT * \delta * LR1$	2.4401
Direct labor cost -ZS ($): $C_{DL2} = StdT*(1-\delta) * LR2$	0.000
Total direct labor cost ($): $CC_{DL} = C_{DL1} + C_{DL2}$	2.4401
Indirect cost estimation:	
Volume range: *VR*	120K
Burdened labor rate - HK ($/hour): *LOH1*	1.313
Burdened labor rate - ZS ($/hour): *LOH2*	0.550
Burdened labor rate - HK/ZS ($/hour): *LOH3*	0.900
Total overhead cost ($): $CC_{OH} = StdT * \delta * LOH1$	1.1368
$+ StdT * (1-\delta) * LOH2 + StdT * LOH3$	
Total Product Costs ($): $C_P = CC_M + CC_{DL} + CC_{OH}$	19.4744

As for requirement management, FR patterns are derived from the functional view of the PFA. Based on these FR patterns, product definition can be enhanced in terms of facilitating the negotiation and interaction among customers, marketing and engineering. Figure 25 shows the elicitation of customer needs with the aid of the FR topology for power supply design, which helps customers articulate requirement information in completeness. FR templates offer a structural and complete mechanism for defining product specifications, as shown in Figure

26. With a PFA as the backbone, the PDFR methodology can lay the foundation of “virtual design by customers”, as envisioned in Jiao (1998).

Figure 25. FR Topology-Aided Customer Needs Elicitation

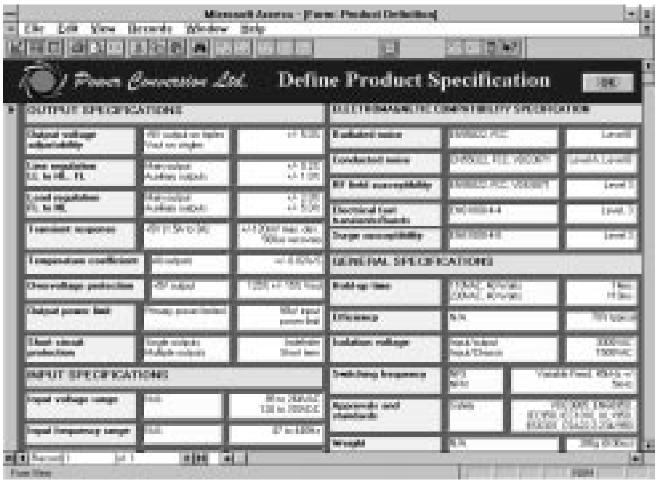


Figure 26. Defining Product Specifications Based on FR Templates

7. CONCLUSIONS

The design for mass customization (DFMC) framework consists of the development of product family architecture (PFA) and the PFA-based product development life-cycle (PFA-PDLC). In the PFA methodology, customer needs are matched with a company’s capabilities through systematic planning of functional diversity and engineering reusability in terms of building blocks and their configuration structures with the synergistic consideration of the functional, behavioral and structural perspectives. The PFA-PDLC resembles DFMC as a type of configuration design in that varieties are accommodated by a limited number of building blocks and their combinations, so that meeting diverse customer requirements and maintaining economy of scale can be achieved simultaneously. Preliminary results from case studies have shown some promising benevolence of developing PFA for mass customization.

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