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Article in *Journal of Intelligent Manufacturing* · March 1999

DOI: 10.1023/A:1008926428533

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# A methodology of developing product family architecture for mass customization

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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 replace old products constantly 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 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. Fig. 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-medium production volumes can gain an edge over competitors by implementing mass customization.

### 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 em-

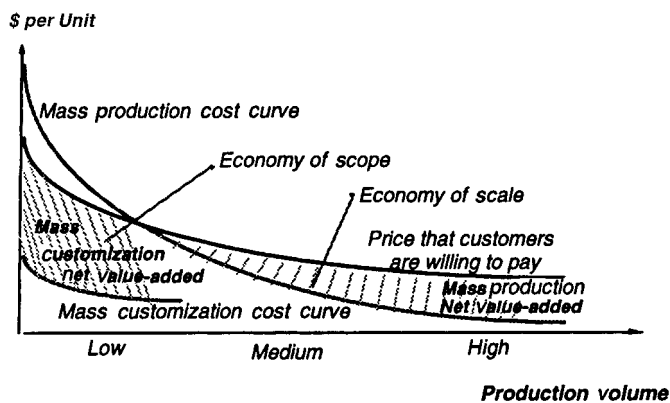


Fig. 1. Mass customization: economic implications.

ulating 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 been identified.

### 1.2.1. 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 towards 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).

### 1.2.2. Product platform

The importance of product development for corporate success has been well recognized (Roberts and Meyer, 1991; Meyer and Utterback, 1993). 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 interrelationships 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).

1.2.3. 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 satisfy various product life-cycle concerns simultaneously, 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 modelling 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 fulfil 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 modelling the design process of a class of products that can widely variegate designs based on individual customization requirements within a coherent framework. Fig. 2 illustrates 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 Fig. 3, various concerns of a PFA, including functionality, technological feasibility and manufacturability, are dealt with by particular views.

2.1.1. Functional view

The functional modelling for a single product has been widely investigated, such as structural analysis (Hatley and Pirbhahi, 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 that 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 rec-

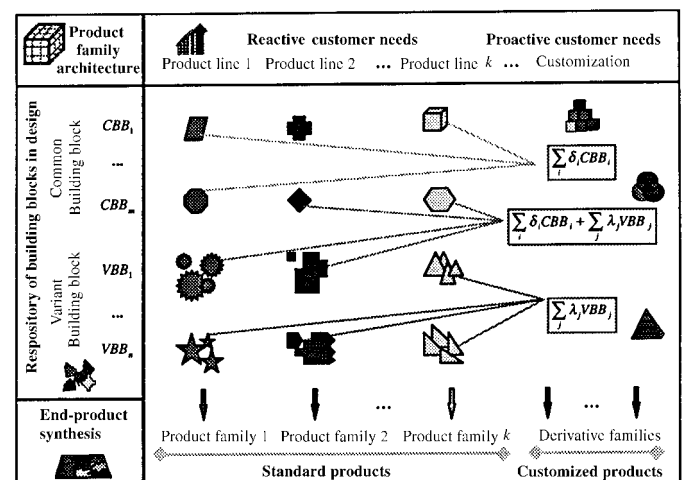
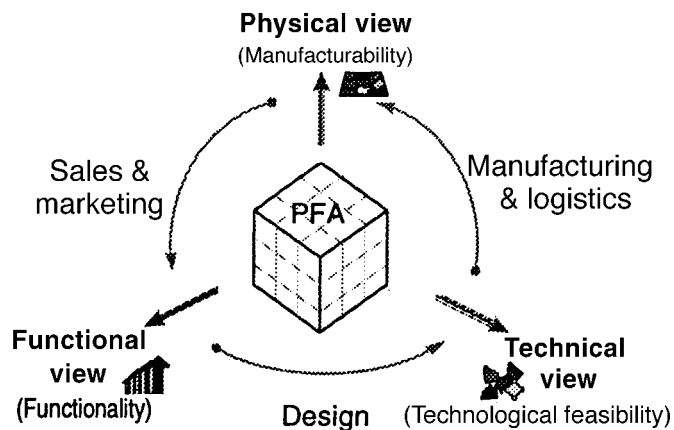


Fig. 2. The principle of PFA-based product development for mass customization.



Views -- Integration of different phases of product development  
 Mappings between views -- Integration of different business functions

Fig. 3. Structural implications and multiple views of a PFA.

ognition 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 modelling of a PFA include customer segmentation, product strategies, competition analysis, technological trends and so on.

### 2.1.2. 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 modelling, 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 modelling 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.

### 2.1.3. Physical view

The physical view is similar to Eren and Verhulst'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 CA 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.

## 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 (Fig. 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 limitations, 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., that 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. Because 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 and 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 of 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 that 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 object (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 reveals the source and migration of varieties involved in different views of a PFA. Fig. 4 and Fig. 5 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; Meyer and Utterback, 1993; Sanderson, 1995), 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 as-

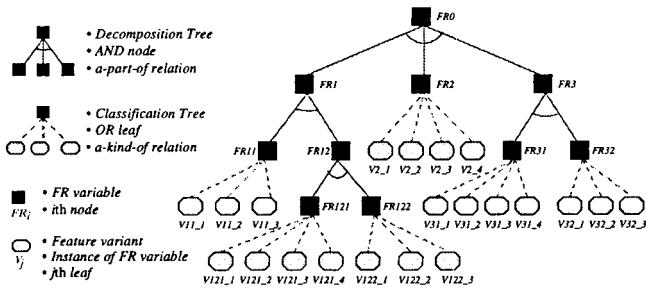


Fig. 4. The and/or tree representation of the functional view of a product family.

assumptions associated with the market and engineering practice for industrial products are observed next.

The market for industrial products has the following features that 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 economic criteria.
- (3) Because 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 modelling through customer requirement analysis (phase 1)

In the functional view of a PFA, a rigorous product line structure depends on a gestalt analysis of product re-

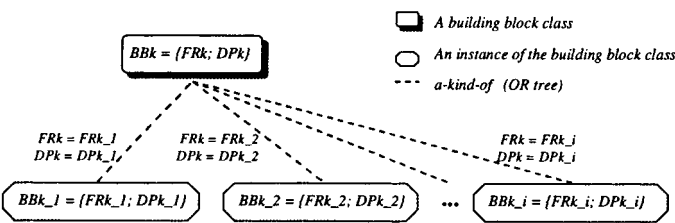


Fig. 5. Representation of a building block class and its instances.

quirements, 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 that consists of FR variables and their interrelationships. The formulation of FR interrelationships can apply knowledge acquisition processes often used in the development of artificial intelligence (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 inducted 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 catalogue design targeting diverse market niches (Meyer and Utterback, 1993). Because 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, 1997b) 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 customer. 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 through 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 customers 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  $i$  ( $\forall j = 1, 2, \dots, n$ ) as follows:

$$d_{j,j+1} = \left\{ \sum_{i=1}^n \left[ w_i \left( \frac{FR_{i,j}^* - FR_{i,j+1}^*}{\overline{FR}_i} \right)^2 \right] \right\}^{1/2} \quad (1)$$

where  $\overline{FR}_i = (\sum_{j=1}^m FR_{i,j}^* / m)$  is the standard value of product attribute  $i$ , introduced for evaluating product 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 fuzzy  $C$ -means (FCM) clustering analysis (Gu and Dubuisson, 1990). This 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, i.e. the variation  $d_{j,j+1}$ , 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 planning product family

Through functional classification, similar customers in terms of their desired values for a FR variable comprise a cluster that is characterized by a representative centre 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 that is used as the target FR value for a planned product variant. Because mostly more than one FR variable is involved, the representative FR values should be derived from the centre 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. Representations 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 structures 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. Fig. 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 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 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  $\overline{FR}_{\text{Product\_Family}} = \{FR11, FR121, FR122, FR2, FR31, FR32\}$ , 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.  $\overline{FR}_{\text{Product\_Variant}}^* = \{V11_{-1}, V121_{-2}, V122_{-3}, V2_{-4}, V31_{-1}, V32_{-3}\}$ .

In summary, the functional modelling of a PFA sets the targets for product family design. Customer grouping determines the type of 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 modelling through modularizing technological solutions (phase 2)

Technical modelling 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 fulfil 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 corresponding FR–DP relationships, matrix decomposition techniques (Pimpler 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 trade-offs in design decision making. Furthermore, this module analysis can be performed at any level of abstraction as appropriate along the FR and DP hierarchies. Fig. 6 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.

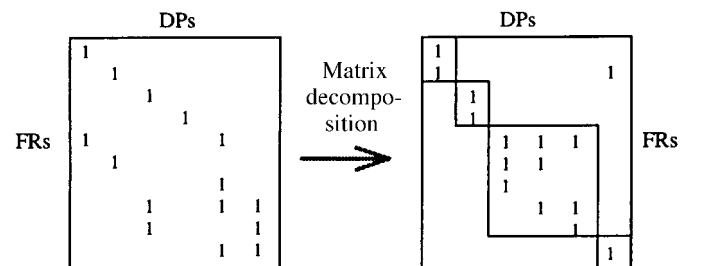


Fig. 6. Design matrix decomposition for technical modularity.

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

### 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.  $FR_{k,i}$ . Fig. 5 illustrates such a representation of building blocks.

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

## 3.4. Physical modelling through economic evaluation of physical modules (phase 3)

In physical modelling, the technical modularity is realized in terms of physical product structures. Components and subassemblies (CAs) are determined according to design modules identified in technical modelling. 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 modelling.

### 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 module 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 block in terms of DPs) is possible to be realized by more than one physical module (building block 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 Fig. 7, the utility,  $U_{ij}$ , of a physical module,  $i$ , for its functional attribute,  $j$ , i.e.  $FR_{ij}$ , responds 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 performances becomes more preferable than the desired value, i.e.  $DoS_{ij} > 0$ , the change of increase

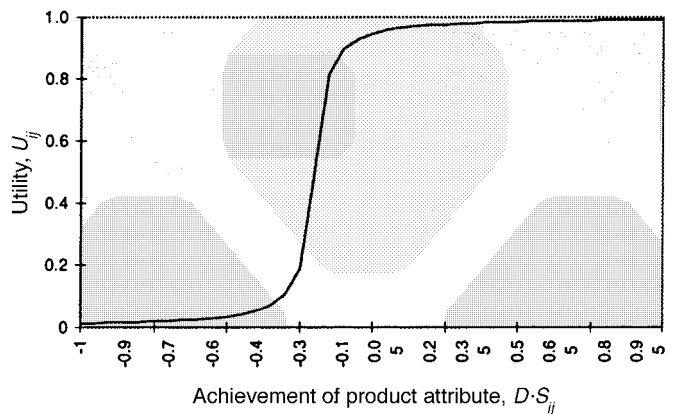


Fig. 7. Performance evaluation based on the utility of a product attribute. (Yoshimura and Takeuchi, 1994).

in  $U_{ij}$  becomes smaller. A widely used function resembling the response curve shown in Fig. 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  $\alpha$  and  $\beta$  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  $DoS_{ij}$  increases (the-more-the-better), and  $\lambda = -1$  if the functional attribute,  $FR_{ij}$ , is more preferable when the value of  $DoS_{ij}$  decreases (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 Equation 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 one, whereas  $U_i$  has a small value close to zero when  $w_{ij}$  is large for low individual utility,  $U_{ij}$ . For low  $w_{ij}$ ,  $U_i$  always has a close to one.

The composite utility,  $U_i$ , defined in Equation 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 one. On the other hand, the lower level is for each attribute value compared with the target value, the further the module's utility value decreases from one and, of course, the value is smaller.

Because 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 follows:

$$U = \left[ \sum_{i=1}^m (V_i U_i) / \sum_{i=1}^m V_i \right] \quad (5)$$

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

### 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, 1997a). 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 pair-wise overall ratings for building blocks. For illustrative simplicity, here we present a pragmatic tool, a  $C-U$  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 zero to one. 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 Fig. 8.

As shown in Fig. 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 are referred to as common building blocks (CBBs), which perform 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

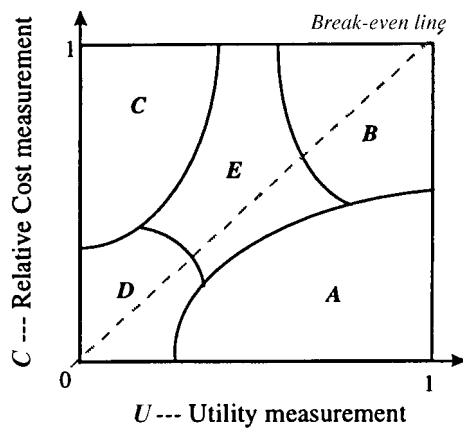


Fig. 8. The C-U plot for building block evaluation (modified from Ishii *et al.*, 1995a).

utilities. These building blocks should be discarded to avoid non-cost-effective differentiation.

(5) When a building block falls into region E, the design needs to be improved towards region A.

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 products variants are derived from the combination (configuration) of the physical modules and the 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 single product modelling, a polyhierarchical node-arc graph (Kohlhase and Birkhofer, 1996) can be used to describe the configuration structure for a product family. Fig. 9 shows such a graph representation of the configuration structure for a product family, which can be considered as the adaption 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.

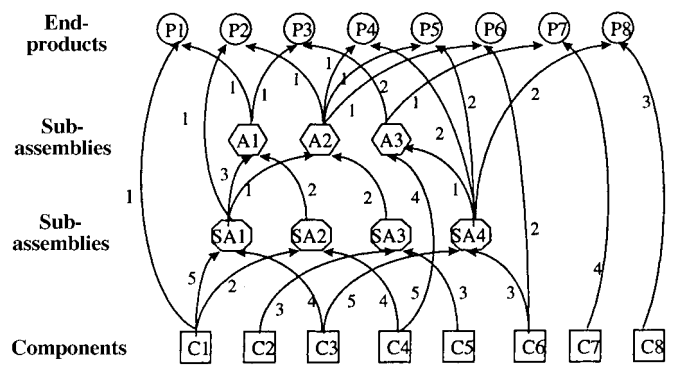


Fig. 9. A graph representation of the configuration structure for a product family.

4. A case study

A power supply company under our investigation offers various products covering a range of more than 1200 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 endeavour 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. Fig. 10 shows examples of power supply products.

4.1. *Phase 1: functional modelling 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

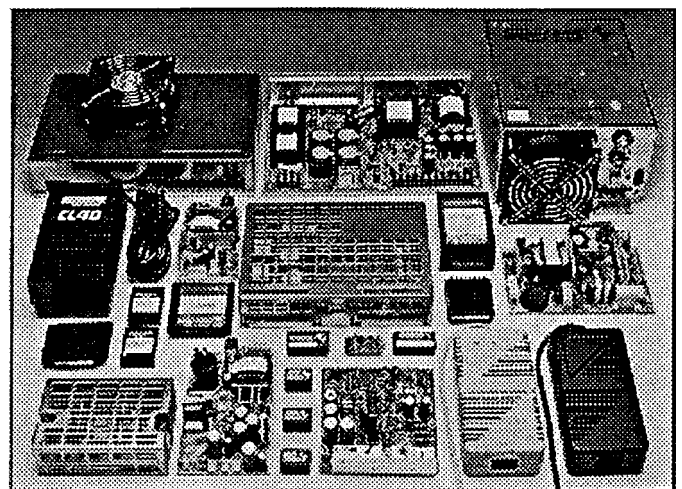


Fig. 10. Various types of power supply products.

(Tseng and Jiao, 1997b). For illustrative simplicity, here we only give FR formulation for the low power A.C.–D.C. converters (Table 1). This category of low power A.C.–D.C. converters actually results from the customer grouping procedure described in Section 3.2.4. Other customer groups include, for example, medium power A.C.–D.C. converters and D.C.–D.C. converters. Different customer groups have quite different sets of FRs in the power supply sector.

According to these FRs, more than 300 existing product models belonging to the customer group of low power A.C.–D.C. converters are instantiated into various FR instances. Since these FR 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 cluster of functional

specifications. Fig. 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 values of "total power" (Fig. 11) is set as 40 W, resulting from clustering similar customer requests, such as 35, 32.5, 41, 38 W, etc. In the functional classification, different priorities of FRs and the volumes of customers' requests are taken into account. For instance, the "total power" is of paramount importance among all the FRs.

#### 4.2. Phase 2: technical modelling of PFA

The available technologies for power supply are investigated at this stage. Fig. 12 gives two examples of solution princi-

**Table 1.** An example of FR hierarchy for power supplies for illustrated FRO: universal low power A.C.–D.C. converters

<i>descriptive level</i>	<i>generic level</i>	<i>terminology level</i>	<i>engineering level</i>
FR1: Used in what country (Input requirement)	FR11: Operating range	FR111: Line voltage FR112: Input surge current FR112: Line transient	FR1111: Voltage range
	FR12: Protection	FR121: Inrush current  FR122: Power-line disturbance FR123: Radiative frequency Interference (RFI)/ Surge suppression	FR1221: Brown-out FR1222: Drop-out
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	
	FR24: Protection	FR233: Feedback loop compensation FR241: Over voltage protection (OVP) FR242: Over current protection (OCP) FR243: Short-circuit protection (SCP)	
FR3: Used in what environment	FR31: Operating condition	FR311: Operating temperature (range) FR312: Operating relative humidity	
	FR32: Safety	FR321: Safety approvals FR322: Electronic magnetic interference (EMI) FR323: Safety ground leakage current	
FR4: Used for what application	FR33: Mechanical requirement	FR331: Mechanical outline (Overall dimensions) FR332: Connection/Connector/Electrical pin-out	
	FR41: Reliability	FR411: Mean time between failure (MTBF) hours (Continuous operation) FR412: On/Off cycles (Repetitive operation)	
	FR42: Quality FR43: Efficiency	FR421: Max. failure rate (percent)	

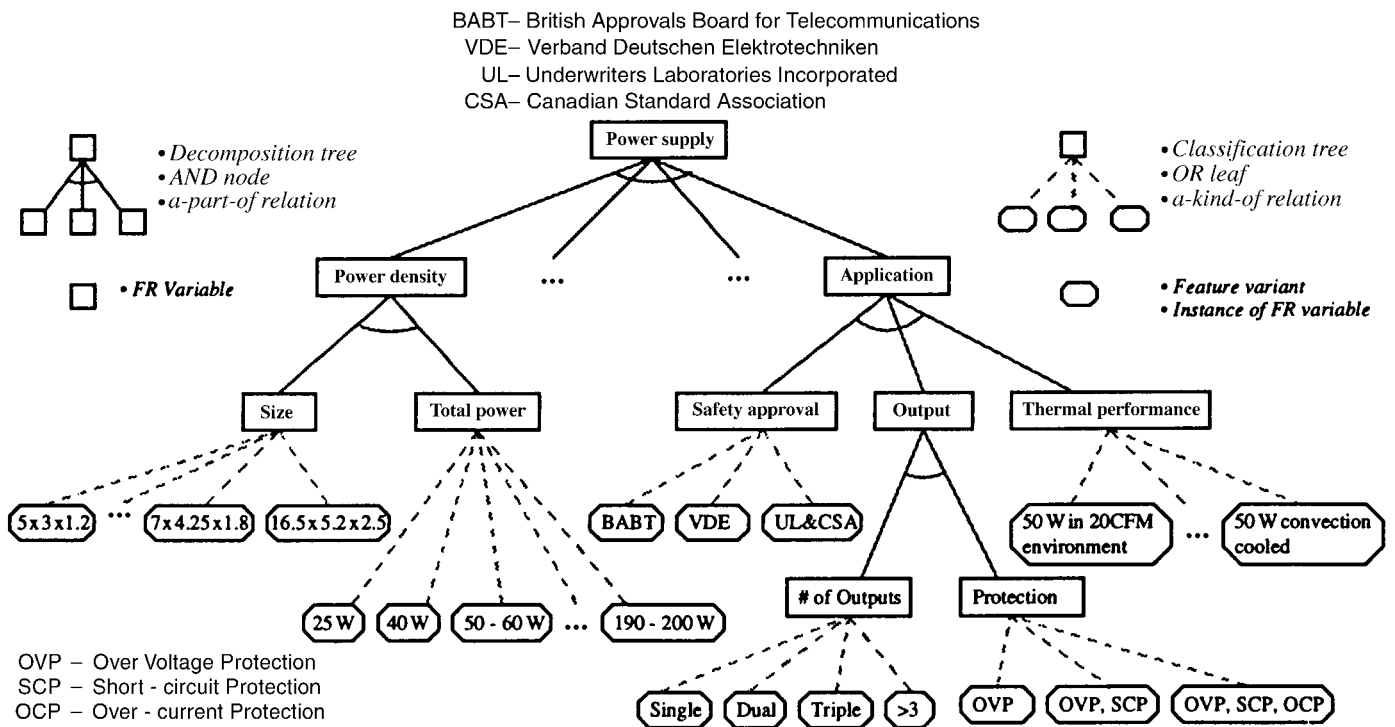
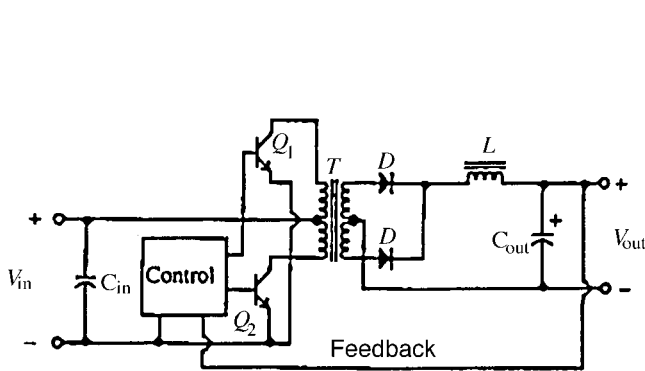


Fig. 11. Representation of the functional view of a PFA for power supply products.

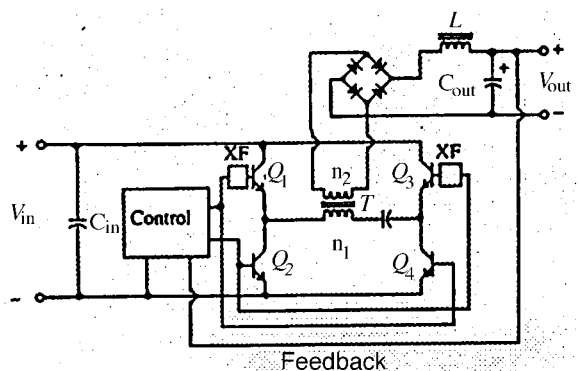
ple, which is often termed as topology in power supply design (Brown, 1994). According to all the target functional specifications of the customer group and considering technological trends and existing process capabilities, one of the many topologies, i.e., the fly-back topology, is selected as the 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 FRs. Table 2 shows the results of DP formulation. The FR–DP mapping relationships are documented in the left half of Fig. 13.

Following the matrix decomposition procedures presented in Section 3.3.3., the design matrix is decomposed into cells (right half of Fig. 13), from which design modules are induced (Table 3). An example of building block representation is given in Table 4. Fig. 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 are configured.



a) The push-pull regulator topology



b) The full-bridge regulator topology

Fig. 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 DP1113: Core size
			DP112: Winding	DP1121: No. of turns DP1122: Wire gauge
		DP12: Power switch	DP121: Types of semiconductors DP122: Ratings of semiconductors DP123: Drive circuit	
		DP13: Output rectifier	DP131: Diode technology DP132: Ratings of rectifiers	
		DP14: Output filtering	DP141: Output capacitors DP142: Physical layout	
	DP2: Control section	DP21: Controller (IC) DP22: Drive circuit	DP15: Input rectifiers	DP151: Input rectifiers
			DP23: Housekeeping circuit	DP221: Zener shunt regulator DP222: Large IC bypass capacitor DP231: Output feedback circuit scheme DP232: Error amplifier DP233: Optoisolator DP234: Resistor divider
			DP31: protection	DP311: Protection scheme DP312: Protection circuit DP321: Bulk input capacitor DP322: Thermistor
	DP3: Ancillary section	DP32: Input filtering		

**4.3. Phase 3: physical modelling of PFA**

For illustrative simplicity, one of the many building blocks, the transformer module, is adopted here to demonstrate the physical modelling of PFA. The design module of the 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. 25, 40, 60 and 100 W. 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 Equation (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.

Fig. 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 Fig. 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 procedure are conducted for all design modules, and thus yielding 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

Initial Design Matrix				Clustered Design Matrix			
DPs	FRs	ID		DPs	FRs	ID	
			123221111321111231231112 331231215231421221314321 21222111113122212241113 1 2 3 1 2				111111331111111222332222 11111522314322212113333 1122122211123 21211234 12312 2
			000000001111111122222 123456789012345678901234				0011010122012201010011 682589071312743446302519
224	1	0000000000010100000100		331	4	0111100000000000000000	
226	2	00100000000000000010000		111	5	1111100000000000000000	
412	3	000000000001000000011		321	26	1101100000000000000000	
331	4	00000010001001001000000		211	18	1011000000000000000000	
1111	5	000001010001001001000000		223	27	1111100000000000000000	
1221	6	00000001100000000000000		43	30	1110100000010000000000	
1222	7	00000001100000010000000		1221	6	0000011000000000000000	
112	8	00010000000000100000000		1222	7	0000011000000000000000	
322	9	10000000000100000001000		121	20	0010001100000000000000	
233	10	01001000010000010000000		123	29	0000010100000000000000	
242	11	00100000000000000001000		224	1	0001000001100000000000	
241	12	00100000000000000001000		322	9	0000000111000000000000	
232	13	01000000010000000100000		225	16	0000000111100000000000	
231	14	01001000000000000001000		221	17	0000000110100000000000	
243	15	00100000000000000001000		412	3	0000000000011100000000	
225	16	10000000000100000001000		411	25	0000000000011100000000	
212	17	10000000000100000001000		112	8	0000000000000000000000	
211	18	00000100000100100100000		113	19	0000000000000000000000	
113	19	00010000000000010000000		222	21	0000000000000000000000	
121	20	00000000100000010000000		332	28	0000000000000000000000	
222	21	00010000000000000000000		226	2	0000000000000000000000	
212	22	01001000000100000001000		242	11	0000000000000000000000	
421	23	00100000000000000001000		241	12	0000000000000000000000	
323	24	00100000000000000001000		243	15	0000000000000000000000	
411	25	00000100000010000000010		421	23	0000000000000000000000	
321	26	00000101000000100100000		323	24	0000000000000000000000	
223	27	00000101000100100100000		233	10	0000000000000000000000	
332	28	00100000000000000000000		232	13	0000000000000000000000	
123	29	00000001000000010000000		231	14	0000000000000000000000	
43	30	00000101000100000100010		212	22	0000000000000000000000	

**Fig. 13.** Design matrix decomposition for technical modularity.

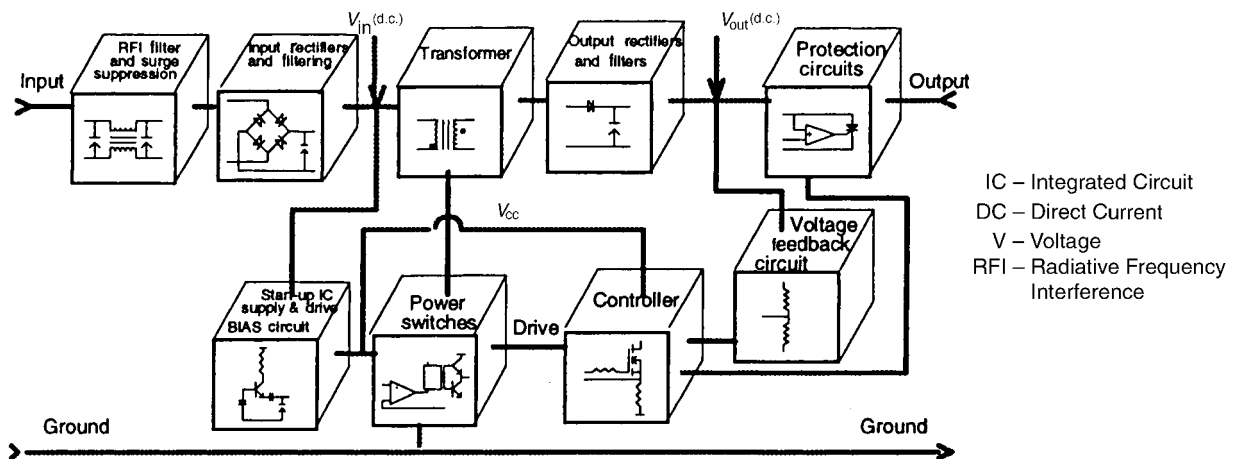
**Table 3.** Power supply design modules

Module	FRs	DPs
Transformer	211	1113
	43	1112
	321	1121
	331	1122
	1111	
	223	
Output rectifiers & filter	123	151
	121	321
	1221	322
	1222	
Startup	43	131
	221	132
	224	141
	225	142
	322	
Power switch & controller	411	121
	412	122
		123
		21
Protection	243	311
	242	312
	241	
	421	
	323	
	226	
Voltage feedback	332	
	112	222
	113	221
Input (rectifiers & filtering & RFI filter/surge suppression)	222	
	212	233
	231	231
	232	232
	233	234

tedious graph representation. In practical production systems, a part coding scheme is usually used to identify different component and subassemblies for modules and/or end products. As illustrated in Table 5, different indented levels conform to the assembly levels from component to subassemblies and to end products. Various building blocks (those with its part code in bold in Table 5) can be either a component or a subassembly and are shared at different levels across the entire product family.

**5. Conclusions**

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 systemic 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 out only unburdening the knowledge base from keeping variant forms of the same solution, but also modelling 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.



**Fig. 14.** An example of a modular structure for power supply design.



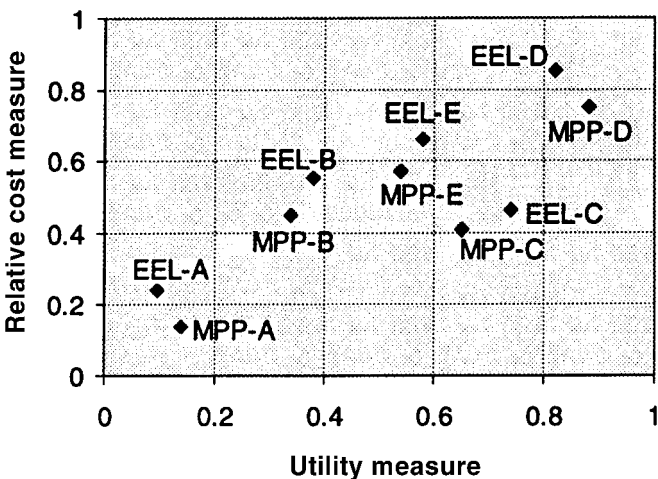
**Table 4.** An example of building blocks in power supply design

<i>FR-DP mapping relationship: <math>FR_k = f_{FR_k}(DP_{k1}; DP_{k2})</math></i>			
<i>Building blocks variants <math>BB_k</math></i>	<i>Building Blocks representation: <math>BB_k = \{FR_k; DP_{k1}, DP_{k2}\}</math></i>		
	<i><math>FR_k</math> Output power (W)</i>	<i><math>DP_k =</math> Magnetic core of transformer</i>	
		<i><math>DP_{k1} =</math> Core Type</i>	<i><math>DP_{k2} =</math> Core Size (mm)</i>
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)

Product family is a well accepted practice in industry. Group technology (GT) traditionally explores and utilizes similarities in manufacturing and production with a 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 efforts 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 labour 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 the type of design work that 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, set-up, process knowledge, etc., according to the building blocks of a PFA, along with interface assessment and configuration optimization.

**Fig. 15.** An example of the economic evaluation of building blocks.

#### Acknowledgements

This research is partially supported by Computer Products Asia-Pacific Ltd (Power Conversion, Hong Kong) under grant CPI 95/96.EG01, the HKUST Research Infrastructure Grant (RI 93/94 EG08), and the Hong Kong Research Grant Council (HKUST 797/96E). The authors would like to express their sincere appreciation to Dr M. Eugene Merchant and Professor Stephen C.-Y. Lu for their valuable advice. Dr W. K. Lo is acknowledged for his continuous support. The reviewers also provided valuable recommendations for revision.

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

Assembly level 1 2 3 4 5 6	Description	Quantity per assembly
720184-001	NFN40-7608 (end product)	1
100020-400	Diode FR 3 A 400 V MR854	1
160010	IC NVR-12 V 1 A 2% TO-220	2
210063-687	Capacitor AL 35 V 680 uF 20%	3
320040-240	Resistor CF 1/2 W 5% 24Ω	1
<b>50041<sup>a</sup></b>	Heatsink NFN40	1
<b>520069</b>	Insulator mica .715 × 1.0	
520069-20	Insulator mica W/O ammo pack	1
640019	Thermal non-silicon heatsink	2
790184-001	Sub assembly-NFN40-7608	1
<b>130088</b>	Xstr NCH mosfet IRF830	1
150002-050	Diode SCR 8 A 50 V	2
30020-332	Resistor CF 1/4 W 5% 3,3 kΩ	3
240019-103	Capacitor CER disk 1 k Ω	1
390012	Thermistor 3 A 15% 10 Ω	1
<b>444801</b>	Fuse CER F H break 3.15 A 250 ΩV	1
<b>510184</b>	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 16 A 45 V	1
160035	IC NVR-15V 1.5	1
210054-188	Capacitor AL 10 V 1800-uF 20%	2
320020-471	Resistor MO 1 W 5% 470Ω	4
<b>500441</b>	Heatsink NFN40	1
<b>520069</b>	Insulator mica .715 × 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
<b>130088</b>	XSTR NCH MOSFET IRF830	1
150005-020	Diode ZNR 1 W 20 V 5% 1N4937	2
380002-501	Resistor var TADJ ST 500 Ω	3
220011-224	Capacitor MPST 63 V .22 uF 5%	1
<b>390012</b>	Thermistor 3 A 15% 10 Ω	1
<b>444801</b>	Fuse CER F H break 3.15 A 250 V	1
<b>510184</b>	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 3/4* BLK	1

<sup>a</sup> Digits given in bold represent building blocks

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