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Computer-Aided Requirement Management for Product Definition: A Methodology and Implementation

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Abstract: Product definition has been recognized as one of the deciding factors in designing a product for success in the marketplace. It involves a tedious elaboration process enacted between customers, marketers and designers. Difficulties associated with product definition for developing product specifications are observed as contextual mismatching, lack of definite structures in requirements, lack of structured mapping, and life-cycle requirements. Facing these difficulties, it is imperative to explore requirement management methodologies and develop computer tools to support requirement management automation.

This paper introduces an approach to requirement management for product definition by evolving from similar existing products. The approach is based on recognizing functional requirement patterns from past design efforts and taking into account product migration, technological trends, competition. A two-phase methodology of functional requirement pattern recognition and pattern adoption is presented in the paper. To facilitate and demonstrate the methodology, a database system is developed to provide a computerized environment for requirement management during the product definition phase. The database system improves product definition during design and redesign efforts by integrating customer and design information all together and by reusing this information. A prototype requirement management database system is implemented for an electronics company to illustrate the feasibility and potential of the proposed methodology.

Key Words: Product Definition, Customer Needs, Product Specification, Functional Requirement, Requirement Management, Design Automation.

1. Introduction

To capture and understand customer needs effectively and subsequently to transfer them into design specifications, namely product definition, is one of the essential premises for successful product design in today's competitive global market (Pugh, 1991). During this phase, the design team explore any combination of customer needs, corporate objectives, product ideas, and related technological capabilities, concluding the process with a definition of the product (Ullman, 1992). Usually, the product’s definition is represented as a list of product requirements, also known as product specifications or target values. This information is often a mix of quantitative values and qualitative descriptions of the product. Usually, only highlights of the design are recorded for future reference, or the company may produce a formal document that may routinely undergo many amendments along with scrutiny, and may require to be signed off by many individuals (Ullman, 1992; Redmond, 1988). Most researchers in the field and industrial designers involve themselves wholeheartedly in the process of mapping from customer needs to design solution, *viz.*, the latter part of the design process subsequent to product definition. However, they are involved only spasmodically and usually highly subjectively in the first part of the design process, *i.e.*, product definition (Redmond, 1988). Even though the issue is of paramount importance, past research has not addressed it well, nor has actual practice helped to formulate means of developing product definition. This paradox results from the formidable hindrances inherent in the product definition process.

1.1 Difficulties in Product Definition

Product definition involves a tedious elaboration process enacted between customers, marketers, and designers. The customer requirements are normally qualitative and tend to be imprecise and ambiguous due to their linguistic origin. In most cases, requirements are negotiable and conflict with each other; tradeoffs are often necessary (Figure 1).

Figure 1 The elaboration/refinement process of product definition

The difficulties associated with product definition to develop product specifications lie in the following aspects: (1) **Contextual mismatching:** Frequently, customers, marketers, and designers employ different sets of contexts to express the requirements. Differences in semantics and terminology impair the ability to convey product requirements from customers to designers due to different perspectives; (2) **Lack of definite structures in requirements**: Variables and their interrelationship with requirements are often poorly understood and are usually expressed in abstract, fuzzy, or conceptual terms, which leads to work on the basis of vague assumptions, resulting in bottlenecks in design decision making; (3) **Lack of structured mapping**: The relationships between customer needs, functional requirements, and design parameters are often not clearly available in an early stage of design. It is difficult, if not impossible, to estimate the consequences (in particular, in terms of economic, scheduling, and quality) of selecting certain requirements; (4) **Life-cycle customer requirements**: Under the concurrent engineering paradigm, the whole spectrum of customer requirements over the product life-cycle needs to be addressed (Prasad, 1996). Customers include anyone downstream of the design team in the product realization process (internal customers), along with end users (external customers).

With the difficulties mentioned above, problems in product design may be observed in many ways. Designers often have to resort to using prototypes, or similar products, to explore customer requirements, which often involves costly and time-consuming hardware fabrication. Customers may not be able to afford the cost burden or time delays. Tradeoffs are made against some requirements with partial information. Some designers have to rush to initiate designs without complete product specifications. Customers are often not aware of the underlying coupling and interrelationships between various requirements with regard to product performance. As a result, less satisfying products have to be accepted by customers, or less competitive products have to be offered by the manufacturers.

1.2 Requirement Management

Product definition has long been a time-consuming and error-prone effort. This is further compounded by the tendency for requirements to be vague and fuzzy and difficult to manage. In addition, in the practice of concurrent engineering, product development teams must keep track of a myriad of requirements derived from different perspectives on the product life-cycle, including manufacturing, reliability, maintainability, and environmental safety, to name but a few. Yet, despite great advances over the past decade in computer-aided design and engineering, there has been relatively little progress in providing analogous support for requirement management (Prasad *et al.*, 1993). As a result, Fiksel and Hayes-Roth (1993) pointed out the necessity to manage requirement information during the product definition process. They defined requirement management as the process of creating, disseminating, maintaining, and verifying requirements.

The requirement management process consists of four main functions that are performed repeatedly in an iterative fashion. They are requirement elicitation, requirement analysis, requirement tracking, and requirement verification (Fiksel and Hayes-Roth, 1993). Requirement elicitation deals with eliciting customers' needs and acquiring the voice of the customers. Requirement analysis is the process of interpreting customer needs and deriving explicit requirements that can be understood and interpreted by people and/or computer programs. Requirement tracking involves continuous interchange and negotiation within a project team regarding conflicting and changing objectives. Requirement verification embodies the procedures for determining whether or not a product design complies with a designated set of requirements.

Apparently, requirement management automation will facilitate a more structured product development process, and at the same time, a more effective integration of humans and machines that reduces product development costs and cycle time while improving product quality. Engineers will be able to comprehend and articulate better the many relationships and tradeoffs among product requirements and different technical approaches. It has been foreseen that, as companies review and enhance their product development processes, they will increasingly demand various types of automated requirement management capabilities (Fiksel and Hayes-Roth, 1993). As a result, to improve product definition, it is imperative to explore requirement management methodologies and develop computer tools to support requirement management automation.

1.3 Related Work

As pointed out by Stauffer and Morris (1991), current practice in product development needs to be enhanced in two key areas: eliciting customer requirements and defining product specifications based on the customer requirements. Approaches to defining product specifications by capturing, analyzing, understanding, and projecting customer requirements, sometimes called the Voice of the Customer (VoC), have received a significant amount of interest from both academia and practitioners in recent years (Gause and Weinberg, 1989; Fung and Popplewell, 1995). A method used for transforming the VoC to product specifications is developed by Ofuji *et al.* (Shoji *et al.*, 1993), in which semantics methods, such as the KJ method (affinity diagram) and MPM (multipickup method), are applied as the basis for discovering underlying facts from affective language. Kano *et al.* (1995) develop systematics to categorize customer requirements for product definition.

To this end, marketing researchers have emphasized customer profiling by applying regression analysis to compare customer characteristics to determine their overall rankings in contribution towards profitability (Jenkins, 1995). Traditionally, market analysis techniques are adopted for investigating customer responses to design options. For example, conjoint analysis is widely used to measure preferences for different product profiles and to build market simulation models (Dobson and Kalish, 1993). Related work by Louviere *et al.* (1990) uses discrete choice experiments to predict customer choices pertaining to design options. Turksen and Willson (1993) employ fuzzy systems to interpret the linguistic meaning regarding customer preferences as an alternative to conjoint analysis. Others have taken a qualitative approach and used focus groups to provide a reality check on the usefulness of a new product design (LaChance-Porter, 1993). Similar techniques include one-on-one interviews and similarity-dissimilarity attribute rankings (Griffin and Hauser, 1992). While these types of activities are helpful for discovering the VoC, it is still difficult to obtain design information because marketers do not know what engineers need to know. They fail to facilitate the synchronization of marketing and engineering to coherently develop product definitions. Thus, these methodologies are not evident in a concurrent engineering context (Veryzer, 1993).

In the engineering community, a technique widely used to join the marketing and engineering efforts is Quality Function Deployment (QFD). A key component of QFD (Clausing, 1994) is the customer requirements frame to aid the designer's view in defining product specifications. While QFD excels in converting customer information to design requirements, it is limited as a means of actually discovering the VoC (Hauge and Stauffer, 1993). To empower QFD with marketing aspects, Fung and Popplewell (1995) propose to pre-process the VoC prior to its being entered as customer attributes into the House of Quality. In pre-processing, they adopt an affinity diagram (KJ method) to categorize, and the Analytic Hierarchy Process (AHP; Satty, 1991) to prioritize the customer requirements. Fukuda and Matsuura (1993) also propose to prioritize the customer's requirements by AHP for concurrent design. Researchers at IBM have used structured brainstorming to build customer requirements into the quality function deployment process (Byrne and Barlow, 1993).

From a design perspective, Hauge and Stauffer (1993) develop a taxonomy of product requirements to assist in traditional qualitative market research. To elicit knowledge from customers (ELK), the taxonomy of customer requirements is deployed as an initial concept graph structure in the methodology for question probe, a method used in the development of expert systems. While ELK aims at making customer information more useful to the designer, the taxonomy developed for ELK is too general to be a domain independent framework. Therefore it is far from accommodating any technical requirements of specific products. The trimming of the taxonomy to map background knowledge is definitely an overwhelming task for substantiating product domain-specific requirements. Thus, it is questionable for a generic taxonomy to have the opportunity to solve real engineering design problems, which are characterized by sophisticated and highly domain-specific customer requirements.

All in all, most approaches assume product development starts from a clean sheet of paper. In practice, however, most new products evolve from existing products. There is little attention paid to evolutionary product design in terms of product definition (Cross *et al.*, 1981). Historical data, the product evolution path, and feedback from customers on current products are often considered only implicitly, if not ignored. As a result, product design seldom has the opportunity to take advantage of the wealth of customer requirement information accumulated in existing products. In addition, with a shortened product life-cycle, expensive investments in product development, and the proliferation of product varieties, the existing approaches are often constrained by the schedule deadline and lack of objectivity in defining product specifications. This results from few methodologies dealing with the tedious and time-consuming aspects of product definition, as well as the complexities and risks inherent in requirement specifications. Furthermore, new product development is facing the challenge of maintaining the continuity of manufacturing and service operations, ***i.e.***, the mass producibility (Tseng and Jiao, 1996). Therefore, product definition should effectively preserve the strength of product families to obtain significant cost savings in tooling, learning curves, inventory, maintenance and so on. This demands a structured approach to product definition and the capturing of gestalt requirement information from previous designs.

1.4 Strategy for Solution

To improve product definition, research efforts need to be geared towards exploring requirement management methodologies and developing computer tools to support requirement management automation (Stauffer and Morris, 1991). To this end, in this paper, we propose a methodology for requirement management during the product definition phase by recognizing functional requirement patterns, noted as PDFR. The PDFR methodology adopts functional requirement patterns from previous product designs to address a broad spectrum of domain-specific customer requirements and to organize requirement information for design specifications. To facilitate and demonstrate the PDFR methodology, we present a database system developed to provide a computerized environment for requirement management during the product definition phase, namely the Requirement Management Database (RMDB) system. The RMDB system is an implementation of the PDFR methodology to improve the product definition process during design and redesign efforts. The prototype RMDB system is implemented on a PC platform by using Microsoft Access database software.

In the next section, the background research leading to the PDFR methodology, upon which the requirement management database system is based, is presented. In Section 3, the system design issues involved in the development of the RMDB system are described, along with a review of existing database technologies. The software selection and the RMDB system implementation are also discussed in Section 3. In Section 4, a case study of product definition in designing power supply products is presented with a focus on the usage of the PDFR methodology and RMDB system. In Section 5, a plan for future work is presented and finally in Section 6 the paper is concluded.

2. Requirement Management Methodology

2.1 Evolutionary Product Design

In order to enhance the reusability of knowledge, evolutionary product design, instead of designing a product from scratch, is frequently adopted in practice (Cross *et al.*, 1981). Here, evolutionary product design implies that new products are evolved from existing products. This is done through modifying the existing product offerings and incorporating specific customer requirements. It is important to utilize past learning from historical data, warranty information, customer feedback, installation, and service records, *etc.* to enhance product features and better serve the customers.

2.2 Functional Requirement

The basis of our approach derives from the understanding of design process as stated by Axiomatic Design (Suh, 1990). It defines the design world as consisting of four distinct domains, *i.e.*, the customer, functional, physical and process domains. The needs of the customers are established in the customer domain. Customer needs are formulated in the functional domain as a set of functional requirements (FRs) that govern the subsequent solution process. The customer domain and functional domain comprise the product definition phase, from abstract customer needs to concrete product requirement specifications, *i.e.* FRs. FRs play an important role in defining product requirements from the perspectives of both the customers and engineers.

2.3 A Variant Approach

Underlying the PDFR methodology is a variant approach aiming at improving the product definition process during design and redesign efforts. The approach assumes that, for certain products, patterns of FRs can be found to represent the generic characteristics of the requirements of existing products. The product definition for a new design can be evolved through modifying existing product designs based on recognized FR patterns from historical data projection.

In the approach, FR patterns consist of FR topology, FR classification, and FR templates, as will be discussed in next section. FR topology enhances the ELK taxonomy (Hauge and Stauffer, 1993) in assisting customer requirement acquisition in that FR topology is more specialized to reflect product domain-specific requirements. FR classification embodies and corresponds to a spectrum of product families with different sets of requirements. FR templates help product redesign by providing a history of past designs, thus allowing for easy reuse and inheritance of design knowledge.

The variant approach to product definition can improve design efficiency by streamlining the elaboration process of requirement definition. The effectiveness of design rationale can be further enhanced by applying FR patterns incorporated with domain-specific knowledge. The advantage is not only a reduction of the designers' workload but also a prevention of the overlooking of relevant information about product requirements. It is also possible to judge automatically whether or not requirement specifications have become concrete enough so that a formal approach to design realization can be applied.

Limitations associated with the approach include: the variant product definition approach is limited to similar products previously designed, *i.e.* the approach is not applicable to innovative designs where there are technological breakthroughs; experience and human judgment are still required to modify FR templates for a specific design; and by no means, the variant approach is not developed to substitute interacting with customers. But rather, it aims at alleviating the difficulties. In addition, there is a risk that adoption of FR patterns for new product design could institutionalize old and noncompetitive designs (including product technology and marketing processes). Therefore, the product development team should assess competition in the marketplace and incorporate appropriate new technological trends to refine FR patterns before they are adopted for new products.

2.4 A Two-Phase Methodology

The PDFR methodology is divided into two phases, *i.e.*, the FR pattern recognition phase and the FR pattern adoption phase, as shown in Figure 2. The FR pattern recognition phase is a preparatory stage, in which FR patterns are extracted from historical data regarding existing designs. These generic FR patterns, essentially representing a set of FRs for a spectrum of products in a company, can then be used to develop product specifications for new designs in the FR pattern adoption phase.

Figure 2 A two-phase methodology of the variant approach to product definition

2.5 FR Pattern Recognition

2.5.1 FR TOPOLOGY FORMULATION

FR pattern recognition starts from FR topology formulation. The terminological FR variables and the interrelationships among them are referred to as FR topology which depends on specific product domain.

A FR topology implicates the decomposition hierarchy of FR variables and the taxonomy of FRs. The formulation of FR topology involves three steps, *i.e.,* product line rationalization, inductive FRs formulation and deductive FRs refinement.

(1) Product line rationalization. The purpose of positioning existing products is to identify the company's strength by identifying products that do not fit into a flexible environment, have low sales, have excessive overhead demands, are not much appreciated by customers, have limited future potential, and so forth. Positioning analysis may direct a company to drop these unprofitable products or, if "completeness" is important, farm out their manufacture to others when they are not within the company's core competencies. Therefore, product positioning is the basic prerequisite for developing FR patterns. The positioning of existing products based on Pareto analysis is presented by Anderson (1997).

(2) 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 variables 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 (Shoji *et. al.,* 1993). The FRs formulation aims at developing a FR hierarchy which consists of FR variables and their interrelationships. The formulation of FR interrelationships can apply knowledge acquisition processes often used in the development of artificial intelligence systems (Lu and Tcheng, 1990). Note that the formulated FRs are generic to the entire product portfolio, *i.e.,* to all the customers in related market niches.

(3) Deductive FRs refinement based on product strategies. To refine the above FR topology induced from existing products, product strategies are proactively assessed by considering competition, technological migration, market trends, and so on. This deductive stage is very important for defining FR topology in recognizing FR patterns 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).

The process of FR topology formulation, as shown in Figure 3, starts with the highest level of requirements from the customers' perspective to product function. By following a decomposition process suggested in (Suh, 1990) and combining that with experts' inputs, ***FR0*** is decomposed into a set of non-overlapping ***FRi***. FR topology can be expressed as a layered FR vector: $\overline{FR0} = \{\overline{FR1}, \overline{FR2}, \ldots, \overline{FRp}\}$, $\overline{FR1} = \{\overline{FR11}, \overline{FR12}, \ldots\}$, and so on. FR topology defines the generic features to describe the whole spectrum of product offerings of a company. It provides a systematic organization of FRs to define customer requirements for a given product with FR interrelationships built into the decomposition hierarchy.

Figure 3 FR topology formulation

2.5.2 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 (Yoshimura and Takeuchi, 1994). Therefore, to explore customer profiles, a survey is conducted, involving (1) checking the number of planned products for each customer, including forecasted volume; (2) checking specific product attributes (FRs) according to the above formulated FRs for every customer; and (3) checking 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 FR instances to represent specific products. Due to diverse customer specifications, null can be an acceptable value for specific FR variables. Through such a mapping, useful historical data and domain knowledge are incorporated into and represented by FR instances.

2.5.3 FR CLASSIFICATION

Due to product varieties, there is an underlying FR classification pattern corresponding to product families in the spectrum of product offerings. Product series are formed by FR classification over the whole product population. FR classification consists of two steps, namely customer grouping at the product level and functional classification at the requirement level.

(1) Customer grouping. While the formulated FRs are generic to all the customers, different customer groups may require different sets from these FRs for their particular applications. Therefore, the FRs need to be categorized into different sets to characterize specific customer groups. This is consistent with various product series in catalog design targeting diverse market niches.

Since customer profiles have been projected and instantiated by a population of FR instances, a Pareto analysis can be employed to extract key FRs, noted as meta-FRs, for characterizing different customer groups. These meta-FRs are a subset of generic FRs formulated earlier. In addition, qualitative classification dependent upon domain knowledge is often necessary to identify meta-FRs for characterizing different customer groups.

Apart from a set of FRs for a particular customer group, the relative importance of these FRs needs to be explicated according to customer preference. Traditionally, QFD (Clausing, 1994) has been widely used to address the identification and analysis of customer values. In QFD, a house of quality helps to enumerate all the product features in order of their importance to the customers. While the measure of customer preference drawn from the house of quality is rather crude and inconsistent, this research adopts the AHP to weight FRs more rigorously and consistently (Satty, 1991).

In such a way, different sets of FR variables are formulated for various customer groups. The results of customer grouping can be summarized as $CG_i \sim \{(FR_{ij}, w_{ij}) | j = 1, 2, ..., n_i\}$, where CG_i denotes a particular customer group (i), w_{ij} denotes the relative importance of the jth FR of CG_i, and n_i is the total number of FRs in CG_i.

(2) Functional classification within each customer group. For each customer group represented by a particular set of FR variables, even though all the customers share the same set of FRs, various functional varieties could result from different desired values for a particular FR variable (different FR instances). The classification of various FR instances for a particular set of FR variables is referred to as functional classification. The focus of functional classification is commonality analysis through clustering similar FR instances into clusters and representing these FR instances by the base values and variation ranges of the center vectors of clustered classes.

In this research, the fuzzy C-means (FCM) clustering analysis technique (Zimmermann, 1987) is adopted. As a measure of the similarity of customer needs (*i.e.*, FR instances), the distance among the desired values for product attributes (*i.e.*, FRs) 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 $FR^*_{i,j}$ and customer $j+1$'s desired value $FR^*_{i,j+1}$ is defined for this customer group (product family) with product attribute i ($\forall i = 1, 2, ..., n$) as follows:

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

where $\overline{FR^*_i} = \dfrac{\sum_{j=1}^{m} FR^*_{i,j}}{m}$ is the standard value of product attribute i introduced for evaluating products' attribute values having different units on the same scale, and w_i is the weighting coefficient of product attribute i where a greater value is given to a more important product attribute with respect to purchase decision making. All the weights are derived from the AHP in customer grouping. The functional classification procedure by the FCM clustering analysis is completed when the variation of the desired values of the product attributes (that is, the variation of $d_{j,\,j+1}$) in a cluster reaches the upper limit or when the total number of customers (products) reaches the lower bound.

Through FR classification, similar customers in terms of their desired-values for a FR 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 FR 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 FR values of customers in the same cluster are averaged to obtain a base FR value which is subsequently used as the target FR value for a planned product variant. The variation range of a base value is usually determined according to the variation of FR instances within a cluster of customers. Since mostly more than one FR variable is involved, a base FR 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 FRs (Jiao, 1998).

2.5.4 FR TEMPLATE CONSTRUCTION

For each FR class, or product series, an FR template can be extracted from all FR instances with reference to FR topology. At this stage, the FR templates only reflect the historical extraction of existing product offerings without considerations for new products. The final FR templates are constructed by further refining the initial templates in terms of engineering considerations and business strategies in order to guide new designs to follow promising and competitive trends. This is always done by consulting experts to take into account such factors as product migration, technological trends, market competition, and so on. The FR template construction is generic to the entire FR class rather than for an individual design. FR templates are indexed by the instances of specific meta-FRs for different FR classes.

2.6 FR Pattern Adoption

With a collection of FR patterns established, product definition for a new product can be assisted in evolutionary design through the following aspects.

2.6.1 CUSTOMER NEEDS ELICITATION

It is often that customers, even though they are capable of expressing their needs, have difficulties in articulating FRs with completeness. In such a case, FR topology is useful to draw out requirements and to help the customers to consider vital dimensions and variables of FRs in expressing their specific FRs.

2.6.2 FR PATTERN SEARCHING

With customers' inputs of their needs, normally more than one alternative FR patterns can be identified. The issue here is the amount of modification that is needed. Here FR patterns serve as a structured basis for customers to consider the cost and schedule consequence of selecting different alternatives. The objective is to enable the customers and design team, most probably represented by marketing function, to discuss various tradeoffs in an objective manner.

2.6.3 FR SPECIFICATION DEFINITION

The final FR specifications for a new product design will be determined through iterations of interaction between the design team and customers with the assistance of the FR template. Modification will be made to enhance customer satisfaction, yet to maintain the economy of scale and to protect existing investment in design and manufacturing.

3. Requirement Management Database System

Having recognized the importance of improving customer needs elicitation, generating product specifications, and managing this information in product definition, much of the development efforts of the PDFR methodology are geared towards organizing the customer and design information in such a way that it brings together marketing and design engineering in the product definition phase. As a methodology of organizing specifications in engineering, PDFR facilitates the storage and retrieval of customer requirements and product specifications. FR patterns allow for easy reuse of design knowledge by providing a design history. Thus, when filled with appropriate information, they render design teams with the knowledge necessary for defining the requirements for a new product.

3.1 Domain Information Management

The requirement management database (RMDB) is a demonstrative implementation of PDFR methodology to organize effectively customer and design information for product definition. The tasks of the RMDB include integrating customer requirements and product specifications, generating product specifications that will satisfy customer needs, and making the information available for downstream design activities. RMDB employs FR classification patterns to organize various products and a functional decomposition hierarchy to represent customer needs. FR patterns are extracted from product repositories and consist of the FR topology and FR templates corresponding to different FR classifications. To help in the elicitation of customer needs, FR topology is employed to prompt the marketer and the customer for their interactive question probe, which alleviates the bottleneck of domain knowledge acquisition in the product definition process. To assist design engineers to define product specifications, customer needs should be presented in an organized and systematic way. A FR template conforms to a product family and provides a class-member relationship between a product family and a new design. In other words, a new product specification can be defined through instantiating the corresponding class template for specific customer needs. The integration of customers, the marketer, and the design engineer is supported by underlying FR patterns. All FR patterns, used by marketing to probe the customer, are also used to organize customer requirements and design specifications. By doing so, marketing and design engineering share customer information in the identical format and order in a structured manner. A typical product development adopting RMDB is modeled in Figure 4. In this model, both the marketer and design engineer use the same FR patterns to elicit and organize customer needs.

Figure 4 A Product definition activity model based on PDFR methodology and RMDB

3.2 Data Model and Development Software

Popular data models in database management systems include hierarchical, network, relational, and object-oriented. The hierarchical data model allows the user to represent each one-to-many relationship by a parent-child designation. In the hierarchical model, many-to-many relationships can be implemented only in a clumsy way, which often results in a redundancy in stored data (Elmasri and Navathe, 1994). In addition, the operations of insertion and deletion become very complex as a result of strict hierarchical ordering. In practice, there often exist many-to-many relationships between customer needs and design attributes in product definition. Therefore, RMDB cannot be adequately supported by the hierarchical model. Like the hierarchical model, a network schema can directly represent one-to-many relationships. Unlike in the hierarchical model, a record type can be the child of more than one parent. However, in addition to the complexity of the network model (Elmasri and Navathe, 1994), there is a restriction on the configuration of many-to-many relationships in a network model, in which a record type that is the child for a relationship cannot also be the parent for a relationship. The result is a schema that has only shallow levels and is therefore not applicable to RMDB. The relational model has been popularly used owning to its simple tabular data format and convenient support to nonprocedural requests and data independence. Although the object-oriented approach promises to reduce the time and cost involved in software development, it is not yet fully developed to handle complex engineering design tasks (Law *et al.*, 1990). Recently, the trend is to extend the relational model using an object-oriented approach that provides certain features lacking in the relational model (Law *et al.*, 1990). Engineering applications like product design involving team work can benefit from the object-oriented extensions without sacrificing the advantages of the relational model. The Enhanced Entity-Relationship (EER) model (Elmasri and Navathe, 1994) incorporates important concepts from the object-oriented approach into the Entity-Relationship (ER) model to represent more complex requirements of engineering applications.

The end-users of RMDB are the marketers and design engineers, therefore a PC based platform is considered. The same consideration is given to the Windows operating system due to its popularity. The RMDB prototype system is implemented by using Microsoft Access database management tool (User guide, 1994). Microsoft Access 2.0 is a relatively easy to use software package system for the Windows environment with powerful database management capabilities. As a virtual programming tool with strengths in relational database applications, it provides event-driven mechanisms to build graphical user interface easily. Its floating toolbar, along with cue cards and powerful wizards simplify many programming tasks, resulting in a professional looking program.

3.3 Functional Analysis

Requirement analysis is the first step of the database life-cycle. RMDB attempts to support three sets of people: the customers who select product offerings from a company by specifying their wants, the marketers who play an important role in bridging the customers and the engineers to acquire and refine customer requirements, and the engineering designers who define product specifications according to elaborated customer requirements and manufacturing considerations. The functional modeling of RMDB is shown in Figure 5 by using IDEF0. The marketers analyze the customer needs based on the requirement management methodology and then search appropriate FR patterns to elaborate the customer requirements. Often negotiation and interaction between the customers and engineers are necessary to make trade-off among product features, technological feasibility, and production capabilities, as well as cost and lead-time constraints. The designers adopt PDFR methodology to turn to FR templates for defining product specifications for new designs and determine the development plans such as customization decisions. In the RMDB system, PDFR methodology performs as a unifying framework for marketers and designers to organize customer information and define product specifications coherently so as to maintain the integrity of the product families and the continuity of the infrastructure, hence leveraging existing design and manufacturing investments.

Figure 5 The role of RMDB in product definition

3.4 Database Design

Data modeling is an important step following the requirement analysis to help the database designer conceptualize the entities and their relationships. The Entity-Relationship (ER) model for the RMDB system is shown in Figure 6 with the major entities and their relationships. The subsequent logical design aims at obtaining a representation that uses as efficiently as possible the facilities for structuring data and modeling constraints available in the logical design. In the logical design of the RMDB system, the conceptual data schema (ER model) is translated into a logical schema (Figure 7) tailored to the specific database management system (Microsoft Access). All these issues are implemented during the physical database design by using Microsoft Access database software. The RMDB system interacts with the user through various views or forms. The first form, as shown in Figure 8, is the main menu of a prototype RMDB system. The menu structure can be defined according to user identification and task analysis. The menu structure of the RMDB system manifests four sets of tasks as shown in Figure 9. They are product selection, order processing, product specification, and DB maintenance, which convey the customer view, marketing view, engineering view, and system view on the RMDB system, respectively.

Figure 6 ER model for RMDB system

Figure 7 Entity-relationships and data sharing in RMDB

Figure 8 Main menu screen dump

Figure 9 RMDB menu structure

4. A Case Study

Power supply is a key component in electronic products, such as telephone switching PBX, stereo equipment, computers and instrumentation. This section reports a case study conducted for power supply design to practice the proposed methodology.

4.1 FR Pattern Recognition

Following steps in section 2.5 and through comprehensive interviews with domain experts, a FR topology for low power AC/DC (40W) converters is formulated as in Table 1. To identify meta-FRs for characterizing specific customer groups, all general FRs are evaluated for their relative importance with respect to different customer groups. Figure 10 presents an example of exploring customer preference by weighting the associated FRs based on the AHP. A Pareto sort helps identify key FRs as meta-FRs. Thus, different product families can be distinguished and characterized by these meta-FRs.

Table 1 An example of FR topology for low power AC/DC power supplies

Figure 10 An example of identifying meta-FRs based on Pareto sort

For low power AC/DC converters, 15 meta-FRs are identified to describe customer grouping. The name, type and a brief description of each meta-FR are listed in Table 2, as well as an example of the symbolic representation used as input to clustering analysis. By customer grouping, FRs for low power AC/DC converters are classified into 6 classes, thus forming 6 product series within the product spectrum, *i.e. AAA40 class, BBB40 class, BBB40 medical class, CCC40 class, DDD40 class,* and *EEE40* class (aliases are used in the paper for all actual names). As an example, the instances of meta-FRs for AAA40 and CCC40 classes are given in Table 3.

According to above formulated FRs, more than 300 existing product models belonging to the customer group of low power AC/DC 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 grouping similar customer specifications into one cluster and to determine the base values and their variation ranges for each cluster of functional specifications. Figure 11 presents the results of functional classification, in which various base values and variation ranges for each FR variable are determined based on the experts' knowledge as a result of understanding the characteristics of the clustered classes.

Finally, combining information about competition and technological trends, FR templates are extracted and refined for each FR class. As an example, the FR template for AAA40 class is given in Table 4.

Table 2 An example of meta-FRs for low power AC/DC converters

Table 3 Two examples of FR classes for low power AC/DC (40W) converters

Figure 11 The and/or tree representation of FR classification for low power AC/DC converters

Table 4 An example of FR template for AAA40 class

4.2 Applying FR Patterns to Product Design

The assistance of FR patterns to new product design can be illustrated by a design example of a low power AC/DC power supply. The customer, at the beginning, was able to provide partial requirements only regarding his application, including outputs, safety, power density, and power quality, due to their lack of knowledge about power supply design and the underlying coupling of various FRs. At this stage, FRs are too incomplete to initiate the design. Usually, a tedious, interactive negotiation process should have to follow between the customer and the designers to develop a FR specification. By applying the proposed approach, FR pattern recognition and adoption alleviate difficulties inherent in product definition for this design. Starting with preliminary FRs given by the customer, the meta-FRs are first instanced. The meta-FR instance for new design is then sent to the classification program (conceptual clustering) to find the class to which it belongs. The FR template is then retrieved according to this FR class. A complete product specification for this design is then easily defined according to this FR template.

In addition to easing the product definition process, in terms of customer satisfaction, the design's adopting FR patterns even provides customer excitement. Originally, the customer ignored, or was not aware of at all, line transient requirement for their application due to his rudimentary knowledge of power supplies, and specified that the design need only to meet UL and CSA safety approvals. With the aid of FR patterns, the new design delivered not only satisfies the original customer requirements but also provides better performance with line transient and wider safety approvals covering UL, CSA, VDE, and BABT. Even so, the extra offerings to the customer are cost effective at a bargain price because they are standardized in design and production, resulting in little design variation and manufacturing changeover.

4.3 Computer-Aided Requirement Management

Power supplies possess a special trait in product definition common to the industrial products. That is, in addition to the general hindrance illustrated in Figure 1, the product definition is a cooperative effort among the customer, the marketer and the engineer. It seldom can be developed by the customer or engineer alone, like many consumer products. By applying the PDFR methodology, the RMDB system alleviates the difficulties inherent in the product definition for power supply design. The screen shot in Figure 12 illustrates the elicitation of customer needs with the aid of FR topology so as to help customers articulate requirement information in completeness. FR templates offer a structural and complete mechanism for defining product specifications, as shown in Figure 13. The example of a formatted product specification report is given in Figure 14. In RMDB, the FR patterns are extracted from the product repositories and organized by a coding system according to FR classification patterns (Jiao, 1998).

Figure 12 FR topology aided customer needs elicitation

Figure 13 Defining product specifications based on FR templates

Figure 14 Screen shot of a product specification report

5. FUTURE WORK

Design can be described as a mapping process from customer requirements in the functional domain to design solutions in the physical domain (Suh, 1990). RMDB captures requirement information in the functional domain to facilitate product definition. The subsequent design mapping can also be supported by the PDFR methodology if design information can be appropriately represented and organized in the database. That is, the RM database, as shown in Figure 4, is extended to act as an engineering database, along with a comprehensive product repository. In such a way, a concurrent design environment can be established within a coherent framework. Moreover, in evolutionary design, how to find a similar case for a new design is often experience dependent and mostly by trial and error. Case-based reasoning technique has proved promising in finding a similar design for accommodating the new design context, in which PDFR methodology can perform as a fundamental mechanism for case memory organization. With a complete product specification, a similar design can be searched via comparing FRs of existing designs based on their FR classes, or product families. Product affinity analysis is used to compare designs, in which product affinities are calculated both qualitatively with regard to design variations and quantitatively with regard to total product cost. Design variations are measured for existing designs in terms of the discrepancies of their FRs to those of a selected reference model. FR templates and FR instances provide a mechanism to determine FR discrepancies. Design variations are subjectively weighted against the reference model with sophisticated design experience. Total costs for existing designs are captured from historical data in terms of material cost, production cost, overhead cost, *etc.*

6. SUMMARY

In evolutionary product design, where products have already had an installed base or existing product families, the PDFR methodology for product definition can improve design efficiency and quality by alleviating the tedious elaboration process of requirement definition between the customers and designers. FR patterns are applied as a basis for modification to meet specific customer needs while maintaining the integrity of the product family and the continuity of the infrastructure, hence leveraging existing design and manufacturing investments. The application of fuzzy clustering analysis opens opportunities for incorporating expert experience into FR patterns from historical data projection and enhances the ability to explore and utilize underlying domain knowledge more effectively.

The paper has presented a domain independent requirement management database (RMDB) system for organizing information during product definition. It is based on the PDFR methodology to provide a framework for integrating customer and design information and for reusing this information. A prototype RMDB system has been implemented on the PC platform using Microsoft Access database software. An application of RMDB system to power supply design has illustrated the feasibility and the potential of the proposed methodology.

Acknowledgments

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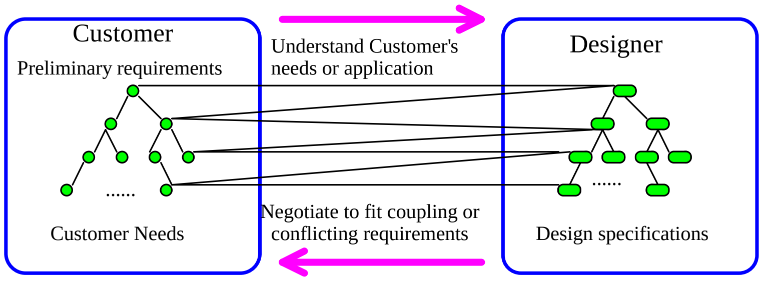


Figure 1 The elaboration/refinement process of product definition

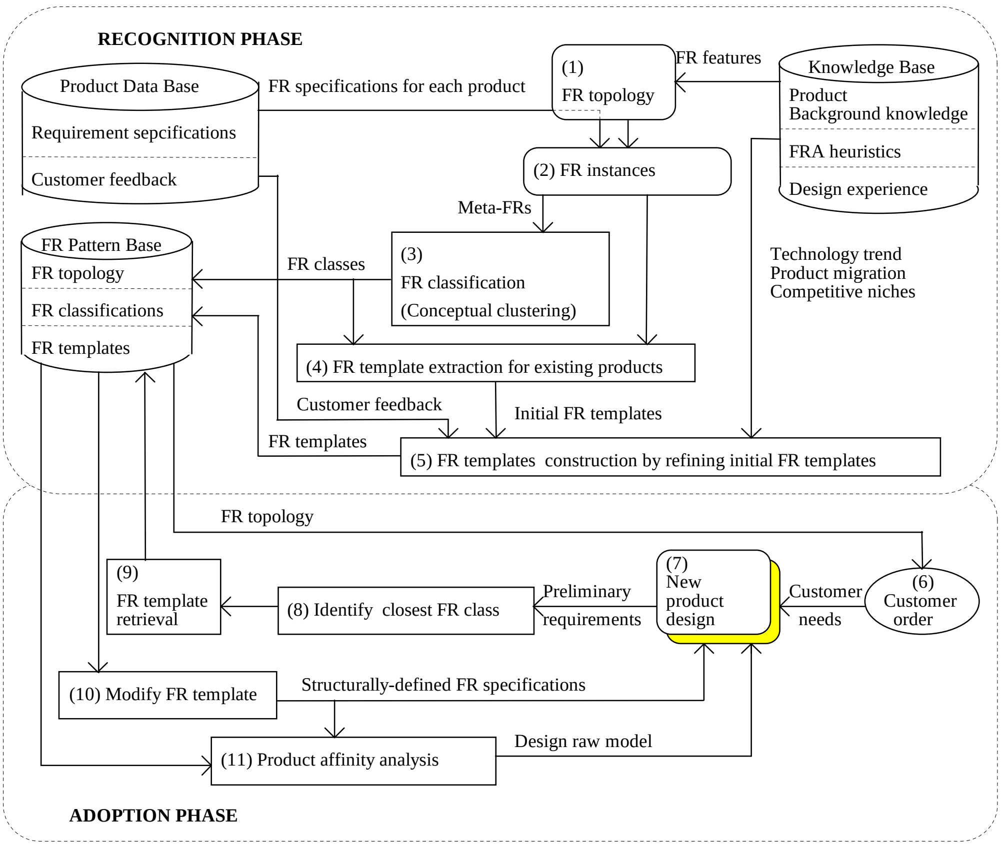


Figure 2 A two-phase methodology of the variant approach to product definition

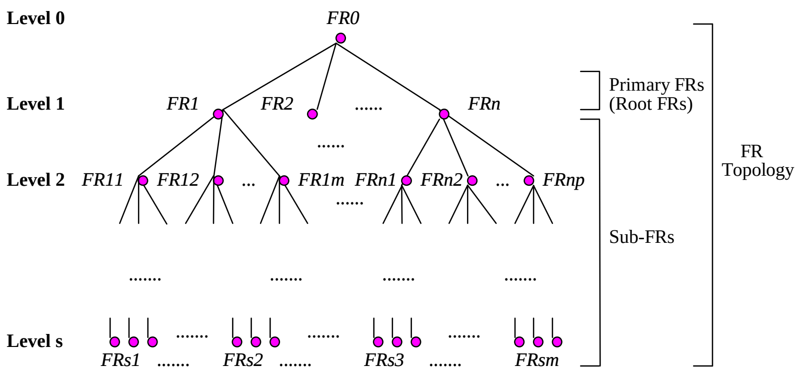


Figure 3 FR topology formulation

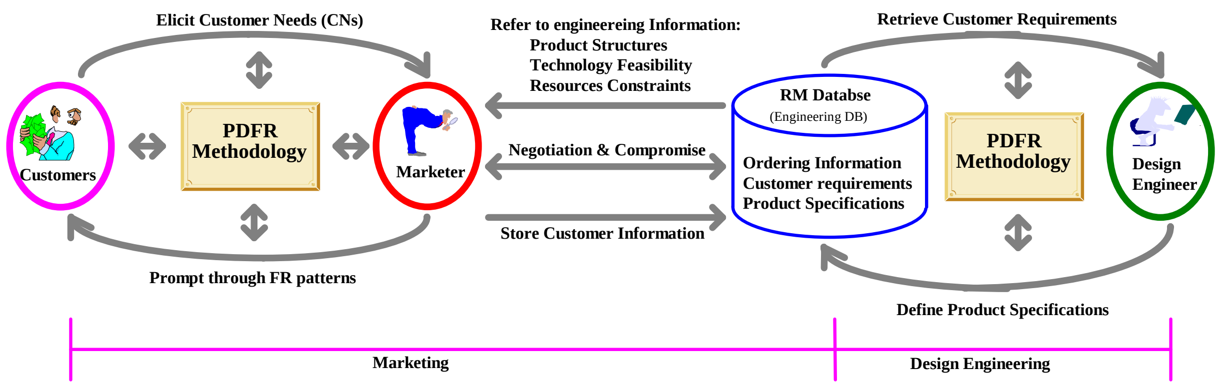


Figure 4 A product definition activity model based on PDFR methodology and RMDB

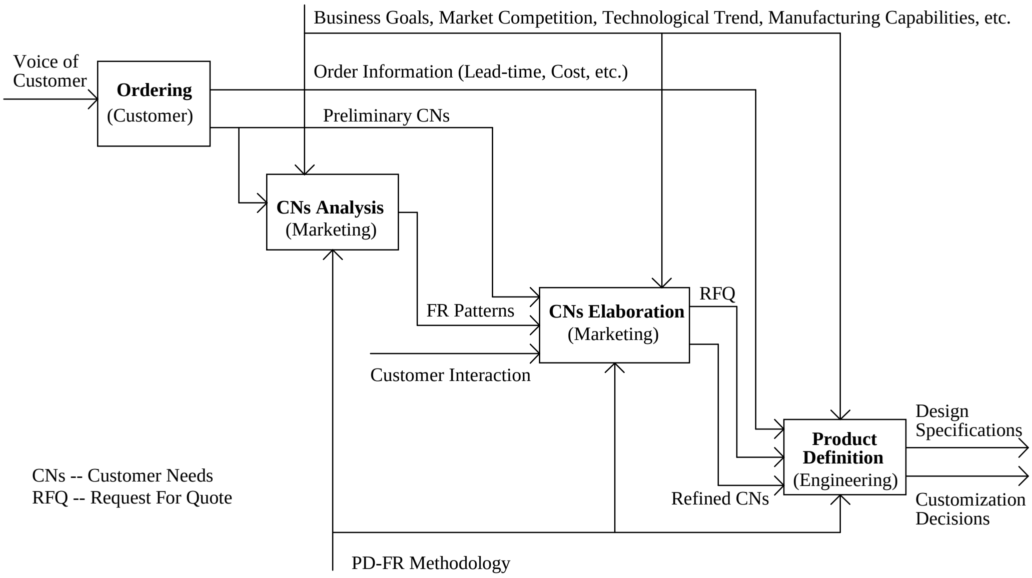


Figure 5 The role of RMDB in product definition

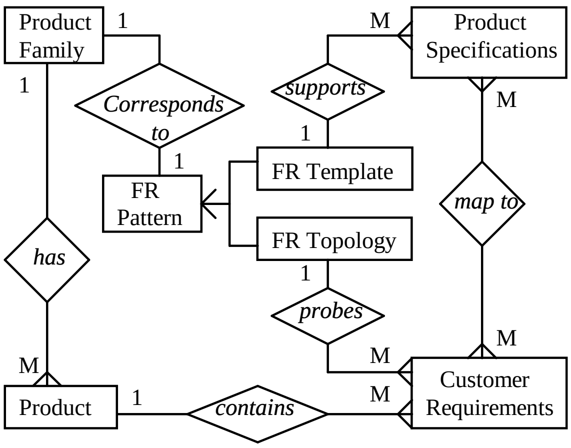


Figure 6 ER model for RMDB system

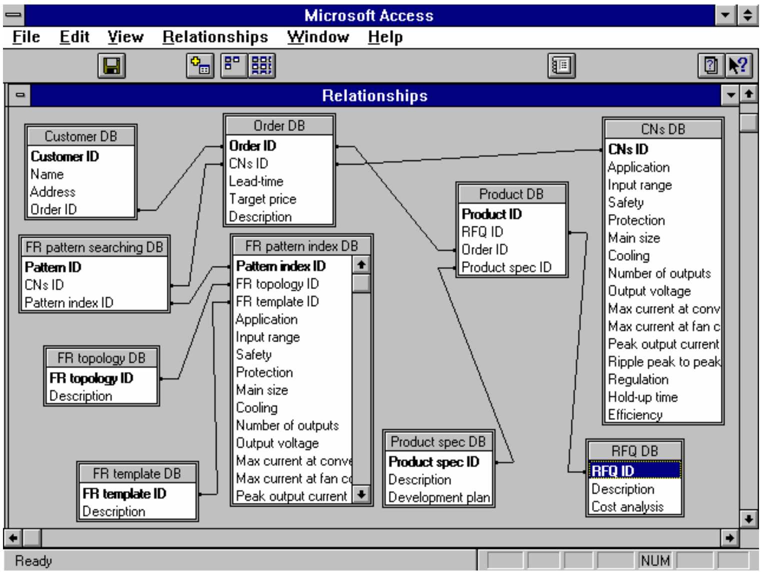


Figure 7 Entity-relationships and data sharing in RMDB

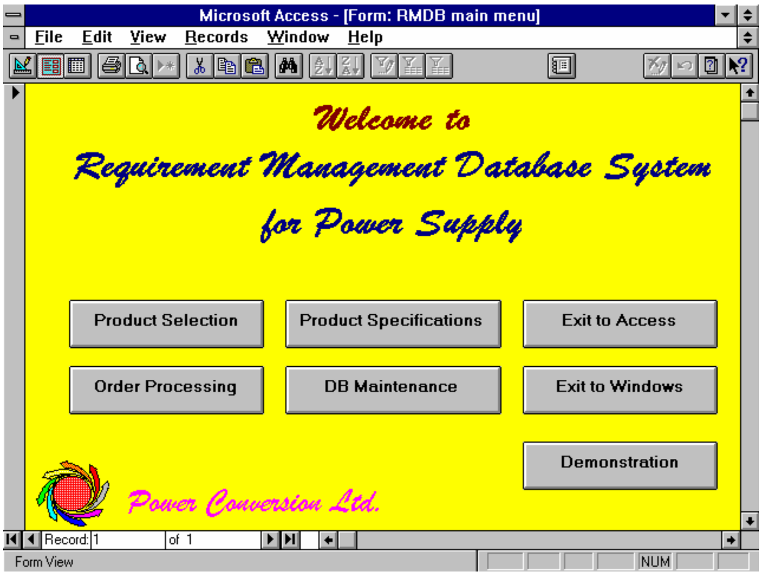


Figure 8 Main menu screen dump

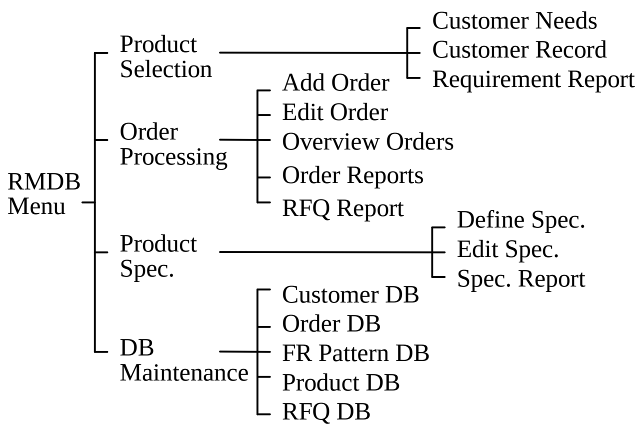


Figure 9   RMDB menu structure

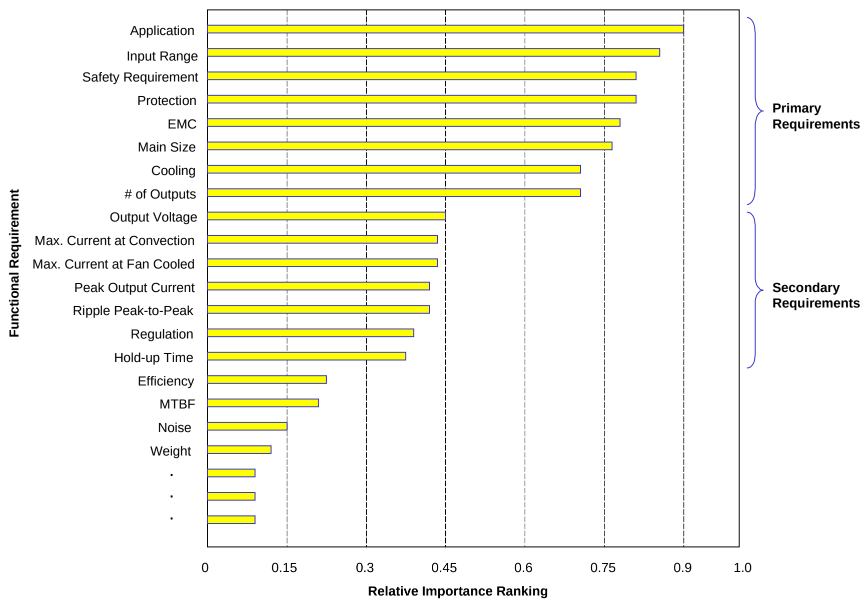


Figure 10   An example of identifying meta-FRs based on Pareto sort

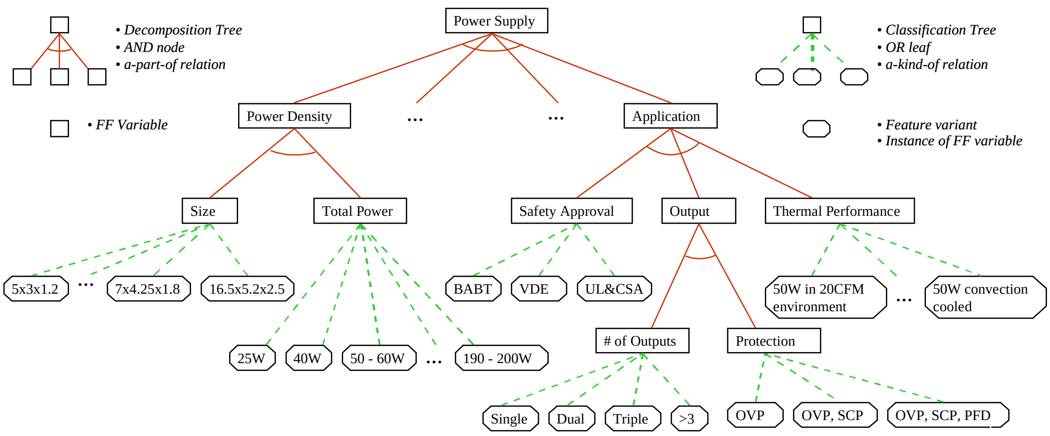


Figure 11 The and/or tree representation of FR classification for low power AC/DC converters

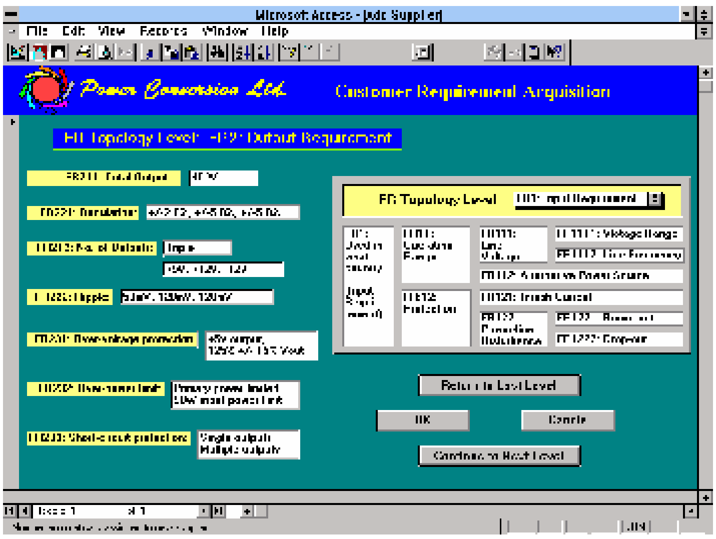


Figure 12 FR topology aided customer needs elicitation

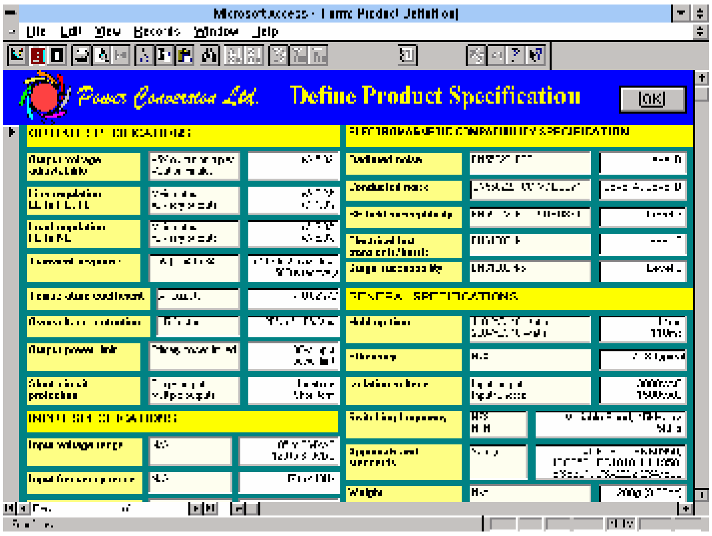
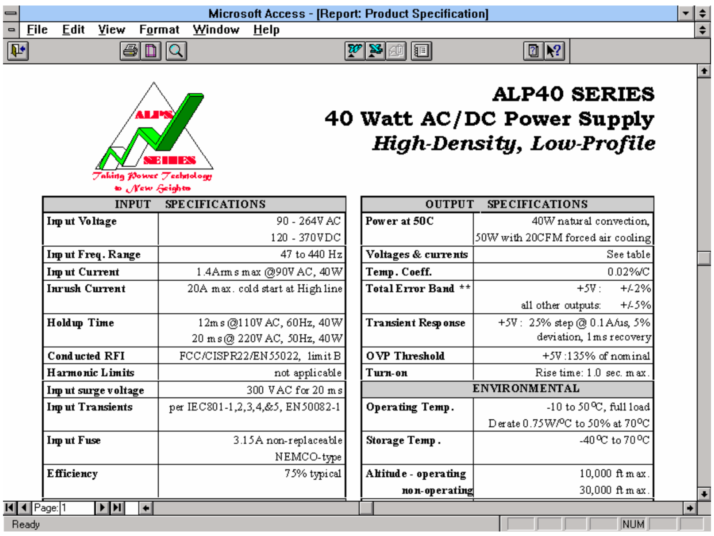


Figure 13 Defining product specifications based on FR templates



ALP40 SERIES
40 Watt AC/DC Power Supply
High-Density, Low-Profile

INPUT SPECIFICATIONS	
Input Voltage	90 - 264V AC 120 - 370VDC
Input Freq. Range	47 to 440 Hz
Input Current	1.4Arms max @90V AC, 40W
Inrush Current	20A max. cold start at High line
Holdup Time	12ms @110V AC, 60Hz, 40W 20 ms@ 220V AC, 50Hz, 40W
Conducted RFI	FCC/CISPR22/EN55022, limit B
Harmonic Limits	not applicable
Input surge voltage	300 VAC for 20 ms
Input Transients	per IEC801-1,2,3,4,&5, EN50082-1
Input Fuse	3.15A non-replaceable NEMCO-type
Efficiency	75% typical

OUTPUT SPECIFICATIONS	
Power at 50C	40W natural convection, 50W with 20CFM forced air cooling
Voltages & currents	See table
Temp. Coeff.	0.02%/C
Total Error Band **	+5V: +/-2% all other outputs: +/-5%
Transient Response	+5V: 25% step @ 0.1A/us, 5% deviation, 1ms recovery
OVP Threshold	+5V :135% of nominal
Turn-on	Rise time: 1.0 sec. max.
ENVIRONMENTAL	
Operating Temp.	-10 to 50°C, full load Derate 0.75W/°C to 50% at 70°C
Storage Temp.	-40°C to 70°C
Altitude - operating **non-operating**	10,000 ft max. 30,000 ft max.

Figure 14 Screen shot of a product specification report

Table 1 An example of FR topology for low power AC/DC 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 FR1112: Line frequency
		FR112: Alternative power source	
	FR12: Protection	FR121: Inrush current	
		FR122: Power-line disturbance	FR1221: Brown-out FR1222: Drop-out
FR2: Used in what system (Output Requirement)	FR21: Power level	FR211: Total output power	
		FR212: No. of output	
	FR22: Power quality	FR221: Regulation/Output voltage range	
		FR222: Overshoot (Turn on overshoot)	
	FR23: Signal	FR231: Signal level	
		FR232: Fan out	

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

Table 2 An example of meta-FRs for low power AC/DC converters

Meta-FRs serve as variables representing FR class features			**Symbolic representation of FRs**
Meta-FRs description	**Classifying variable**	**Type**	**as input to clustering analysis**
Application	application	nominal	application = universal input switcher
Input range	input_range (VAC)	linear	input_range = 85, 264
Safety requirements	safety	nominal	safety = UL,CSA,VDE,BABT
Protection	protection	nominal	protection = overvoltage, short circuit
Main size (L x W x H)	size (mm, mm, mm)	linear	size = 127,76.2,30.5
Cooling	cooling (w)	linear	cooling = 40,50
Number of outputs	output_number	linear	hold_up_time = 14,110
Output voltage	output_voltage (v)	linear	efficiency = 70
Max current at convection	i_max (a)	linear	output_number = 3,
Max current at fan cooled	i_fan (a)	linear	output_voltage = 5.1,12,-12
Peak output current	i_peak (a)	linear	i_max = 3,2,0.35
Ripple peak to peak	ripple (mv)	linear	i_peak = 7,3,1
Regulation	regulation (+/-%)	linear	i_fan = 5,2,0.5
Hold-up time at @110VAC,40W and @ 230VAC,40W	hold_up_time (ms)	linear	ripple = 50,120,120
Efficiency	efficiency (%)	linear	regulation = 2.0,5.0,5.0

Table 3 Two examples of FR classes for low power AC/DC (40W) converters

Meta-FRs	**AAA40 series**	**CCC40 series**
Application	Universal input switchers	Universal input switchers
Input range	85VAC - 264VAC universal input Fixed frequency operation	90VAC - 264VAC universal input
Safety	UL,CSA,VDE,BABT	UL,CSA,VDE,BABT
EMC	EN55022 class B, FCC class B, and VDE0871 class B	EN55022, FCC, and VDE0871 class B
Protection	Overvoltage Short circuit with auto-restart	Overvoltage; Overcurrent
Size	127X76.2X30.5	127X76.2X30.5
Cooling	40W convection, 50W in 20CFM	40W convection, 50W in 20CFM
Outputs	Single; Triple	Single; Dual; Triple

** This table is truncated-given due to space limitations.*

Table 4 An example of FR template for AAA40 class (Only end leaves are shown here)

SAFETY REQUIREMENTS
- Designed to meet:
- UL, CSA, VDE, TUV, BABT, other

ELECTRICAL SPECIFICATIONS (Input AC/DC)
- Voltage [Low, Nominal, High]
- Max RMS Current [Low, Nominal, High]
- Max Inrush/Cold [Low, Nominal, High]

POWER FAIL DETECT
- Max Input Power
- Line Fuse [amps on board]

REGULATION AND RIPPLE
- Nominal Vlotage
- Average Imin
- Transient Response
- OVP Threshold Band [V TO V]
- Burn-in Power with Rated Fan [watts]
- At Min Power [from, to]
- At Max Power [from, to]

GENERAL SPECIFICATION
- Efficiency
- EMI Requirements
- FCC [Designed to meet, Radiated, Conducted]
- VDE0871 [Designed to meet, Radiated, Conducted]
- Leakage Current Requirements [uA @ 132V,60Hz]

MECHANICAL SPECIFICATION
- Main size
- Special markings, labels
- Outline Drawing and Pin-out

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

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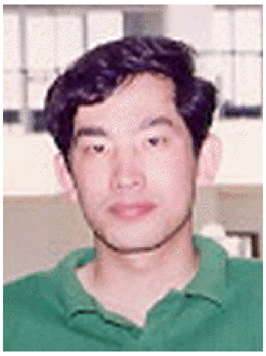
Professor Mitchell Tseng holds a B.S. degree in Nuclear Engineering from the National Tsing Hua University in Taiwan, a M.Sc. degree and a Ph.D in Industrial Engineering from Purdue University. He joined the Hong Kong University of Science and Technology as the founding department head of Industrial Engineering and Engineering Management in 1993 after holding executive positions at Xerox and Digital Equipment Corporation for almost two decades. He previously held faculty positions at University of Illinois at Champaign Urbana and Massachusetts Institute of Technology. His research interests include global manufacturing systems, mass customization, information systems applications, and business process design.

Jianxin Jiao



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