CHAPTER 25

Mass Customization

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1. INTRODUCTION

With the increasing competition in the global market, the manufacturing industry has been facing the challenge of increasing customer value. Much has been done to reduce costs and improve quality. Quality does not mean only conforming to specifications. More importantly, quality means ensuring customer satisfaction and enhancing customer value to the extent that customers are willing to pay for the goods and services. To this end, a well-accepted practice in both academia and industry is the exploration of flexibility in modern manufacturing systems to provide quick response to customers with new products catering to a particular spectrum of customer needs. Consequently, there is a growing trend toward increasing product variety, as evident in supermarkets. Various food and beverage companies are fighting for shelf space to display the explosive growth of product varieties. Rapidly changing design and product technologies further accentuate this trend. The key to success in the highly competitive manufacturing enterprise often is the company's ability to design, produce,

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and market high-quality products within a short time frame and at a price that customers are willing to pay. These counterdemands for final products create enormous productivity challenges that threaten the very survival of manufacturing companies. In addition, increasingly high labor and land costs often put developed countries or regions at a disadvantage in attracting manufacturing plants comparing with neighboring developing countries. In order to meet these pragmatic and highly competitive needs of today's industries, it is imperative to promote high-value-added products and services (Ryan 1996). It was reported that 9 out of 10 bar code scanner vendors were planning to repackage their product offerings in 1997 to include a larger scope of value-added features and pursue application-specific solution opportunities (Rezendes 1997).

This chapter discusses the opportunities brought by mass customization for high-value-added products and services. Mass customization enhances profitability through a synergy of increasing customer-perceived values and reducing the costs of production and logistics. Therefore, mass customization inherently makes high-value-added products and services possible through premium profits derived from customized products. The chapter also introduces techniques of integrating product life-cycle concerns in terms of how to connect customer needs proactively with the capabilities of a manufacturer or service provider during the product-development process. Major technical challenges of mass customization are also summarized.

1.1. Concept Implication

Mass customization is defined here as "producing goods and services to meet individual customer's needs with near mass production efficiency" (Tseng and Jiao 1996). The concept of *mass customization* was anticipated by Toffler (1971) and the term was coined by Davis (1987). Pine (1993) documented its place in the continuum of industrial development and mapped out the management implications for firms that decide to adopt it. Mass customization is a new paradigm for industries to provide products and services that best serve customer needs while maintaining near-mass production efficiency. Figure 1 illustrates the economic implications of mass customization (Tseng and Jiao 1996). Traditionally, mass production demonstrates an advantage in high-volume production, where the actual volume can defray the costs of huge investments in equipment, tooling, engineering, and training. On the other hand, satisfying each individual customer's needs can often be translated into higher value, in which, however, low production volume is unavoidable and thus may lend itself to becoming economically not viable. Accommodating companies to garner economy of scale through repetitions, mass customization is therefore capable of reducing costs and lead time. As a result, mass customization can achieve higher margins and thus be more advantageous. With the increasing flexibility built into modern manufacturing systems and programmability in computing and communication technologies, companies with low to medium production volumes can gain an edge over competitors by implementing mass customization.

In reality, customers are often willing to pay premium price for their unique requirements being satisfied, thus giving companies bonus profits (Roberts and Meyer 1991). From an economic perspective, mass customization enables a better match between the producers' capabilities and customer needs. This is accomplished through either developing the company's portfolio, which includes prod-

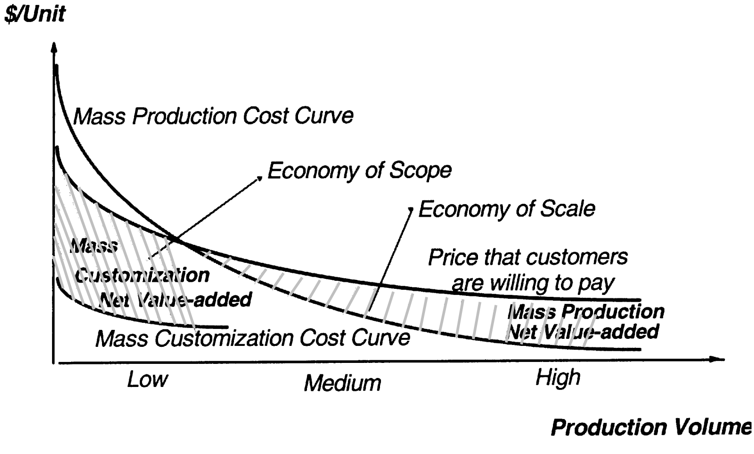

Figure 1 Economic Implications of Mass Customization.

ucts, services, equipment, and skills, in response to market demands, or leading customers to the total capability of the company so that customers are better served. The end results are conducive to improvement in resources utilization. Mass customization also has several significant ramifications in business. It can potentially develop customer loyalty, propel company growth, and increase market share by widening the product range (Pine 1993).

1.2. Technical Challenges

The essence of mass customization lies in the product and service providers' ability to perceive and capture latent market niches and subsequently develop technical capabilities to meet the diverse needs of target customers. Perceiving latent market niches requires the exploration of customer needs. To encapsulate the needs of target customer groups means to emulate existing or potential competitors in quality, cost, quick response. Keeping the manufacturing cost low necessitates economy of scale and development of appropriate production capabilities. Therefore, the requirements of mass customization depend on three aspects: time-to-market (quick responsiveness), variety (customization), and economy of scale (volume production efficiency). In other words, successful mass customization depends on a balance of three elements: features, cost, and schedule. In order to achieve this balance, three major technical challenges are identified as follows.

1.2.1. Maximizing Reusability

Maximal amounts of repetition are essential to achieve the efficiency of mass production, as well as efficiencies in sales, marketing, and logistics. This can be attained through maximizing commonality in design, which leads to reusable tools, equipment, and expertise in subsequent manufacturing. From a commercial viewpoint, mass customization provides diverse finished products that can be enjoyed uniquely by different customers. Customization emphasizes the differentiation among 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 setup presents manufacturers with a challenge of ensuring "dynamic stability" (Boynton and Bart 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. Due to 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. Maximizing reusability across internal modules, tools, knowledge, processes, components, and so on means that the advantages of low costs and mass production efficiency can be expected 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 cycle, such as existing design capabilities and manufacturing facilities.

Although commonality and modularity have been important design practices, these issues are usually emphasized for the purpose of physical design or manufacturing convenience. To achieve mass customization, the synergy of commonality and modularity needs to be tackled starting from the functional domain characterized by customer needs or functional requirements, and needs to encompass both the physical and process domains of design (Suh 1990). In that way, the reusability of both design and process capabilities can be explored with respect to repetitions in customer needs related to specific market niches.

1.2.2. Product Platform

The importance of product development for corporate success has been well recognized (Meyer and Utterback 1993; Roberts and Meyer 1991). The effectiveness of a firm's new product generation lies in (1) its ability to create a continuous stream of successful new products over an extended period of time and (2) the attractiveness of these products to the target market niches. Therefore, the essence of mass customization is to maximize such a match of internal capabilities with external market needs.

Towards this end, a product platform is impelled to provide the necessary taxonomy for positioning different products and the underpinning structure describing the interrelationships between various products with respect to customer requirements, competition information, and fulfillment processes. A product platform in a firm implicates two aspects: 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 terms of mass customization, a product platform provides the technical basis for catering to customization, managing variety, and leveraging existing capabilities. Essentially, the product platform captures and utilizes reusability underlying product families and serves as a repertoire of knowledge bases for different products. It also prevents variant product proliferation for the same set of customer requirements. The formulation of product platform involves inputs from design concepts, process capabilities, skills, technological trends, and competitive directions, along with recognized customer requirements.

1.2.3. Integrated Product Life Cycle

Mass customization starts from understanding customers' individual requirements and ends with a fulfillment process targeting each particular customer. The achievement of time-to-market through telescoping lead times depends on the integration of the entire product-development process, from customer needs to product delivery. Boundary expansion and concurrency become 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 should simultaneously satisfy various product life cycle concerns, including functionality, cost, schedule, reliability, manufacturability, marketability, and serviceability, to name but a few. The main challenge for today's design methodologies is to support these multiple viewpoints to accommodate different modeling paradigms within a single, coherent, and integrated framework (Subrahmanian et al. 1991).

In other words, the realization of mass customization requires not only integration across the product development horizon, but also the provision of a context-coherent integration of various viewpoints of product life cycle. It is necessary to employ suitable product platforms with unified product and product family structure models serving as integration mechanisms for the common understanding of general construction of products, thereby improving communication and consistency among different aspects of product life cycle.

2. DESIGN FOR MASS CUSTOMIZATION

Design has been considered as a critical factor to the final product form, cost, reliability, and market acceptance. The improvements made to product design may significantly reduce the product cost while causing only a minor increase in the design cost. As a result, it is believed that mass customization can best be approached from design, in particular, the up-front effort in the early stages of the product-development process.

Design for Mass Customization (DFMC) (Tseng and Jiao 1996) aims at considering economies of scope and scale at the early design stage of the product-realization process. The main emphasis of DFMC is on elevating the current practice of designing individual products to designing product families. In addition, DFMC advocates extending the traditional boundaries of product design to encompass a larger scope, from sales and marketing to distribution and services. To support customized product differentiation, a product family platform is required to characterize customer needs and subsequently to fulfill these needs by configuring and modifying well-established modules and components. Therefore, there are two basic concepts underpinning DFMC: product family architecture and product family design. Figure 2 summarizes the conceptual implications of DFMC in terms of the expansion of context from both a design scope perspective and a product-differentiation perspective.

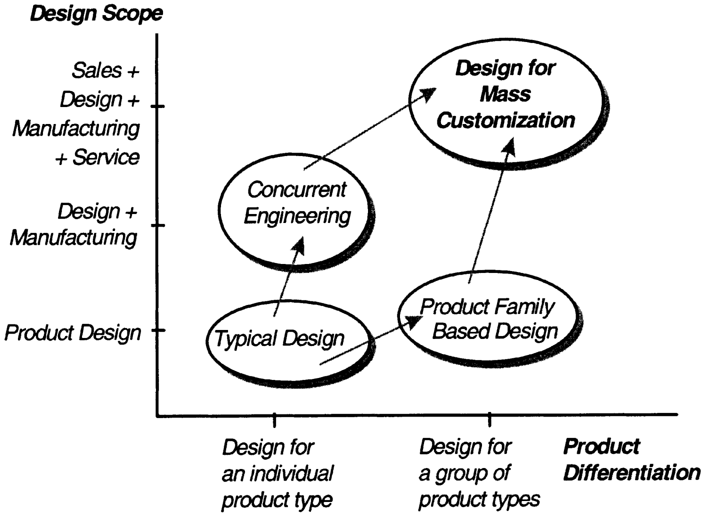

Figure 2 Understanding DFMC.

2.1. Product Family

A product family is a set of products that are derived from a common platform (Meyer and Lehnerd 1997). Each individual product within the family (i.e., a product family member) is called a product variant. While possessing specific features/functionality to meet a particular set of customer requirements, all product variants are similar in the sense that they share some common customer-perceived value, common structures, and/or common product technologies that form the platform of the family. A product family targets a certain market segment, whereas each product variant is developed to address a specific set of customer needs of the market segment.

The interpretation of product families depends on different perspectives. From the marketing/sales perspective, the functional structure of product families exhibits a firm's product portfolio, and thus product families are characterized by various sets of functional features for different customer groups. The engineering view of product families embodies different product and process technologies, and thereby product families are characterized by different design parameters, components, and assembly structures.

2.1.1. Modularity and Commonality

There are two basic issues associated with product families: modularity and commonality. Table 1 highlights different implications of modularity and commonality, as well as the relationship between them.

The concepts of modules and modularity are central in constructing product architecture (Ulrich 1995). While a module is a physical or conceptual grouping of components that share some characteristics, modularity tries to separate a system into independent parts or modules that can be treated as logical units (Newcomb et al. 1996). Therefore, decomposition is a major concern in modularity analysis. In addition, to capture and represent product-structures across the entire product-development process, modularity is achieved from multiple viewpoints, including functionality, solution technologies, and physical structures. Correspondingly, there are three types of modularity involved in product realization: functional modularity, technical modularity, and physical modularity.

What is important in characterizing modularity is the *interaction* between modules. Modules are identified in such a way that between-module (intermodule) interactions are minimized, whereas within-module (inframodule) interactions may be high. Therefore, three types of modularity are characterized by specific measures of interaction in particular views. As for functional modularity, the interaction is exhibited by the relevance of functional features (FFs) across different customer groups. Each customer group is characterized by a particular set of FFs. Customer grouping lies only in the functional view and is independent of the engineering (including design and process) views. That is, it is solution neutral. In the design view, modularity is determined according to the technological feasibility of design solutions. The interaction is thus judged by the coupling of design parameters (DPs) to satisfy given FFs regardless of their physical realization in manufacturing. In the process view, physical interrelationships among components and assemblies (CAs) are mostly derived from manufacturability. For example, on a PCB (printed circuit board), physical routings of CAs determine the physical modularity related to product structures.

It is the commonality that reveals the difference of the architecture of product families from the architecture of a single product. While modularity resembles decomposition of product structures and is applicable to describing module (product) types, commonality characterizes the grouping of similar module (product) variants under specific module (product) types characterized by modularity. Corresponding to the three types of modularity, there are three types of commonality in accordance with functional, design, and process views. Functional commonality manifests itself through functional classification, that is, grouping similar customer requirements into one class, where similarity is measured by the Euclidean distance among FF instances. In the design view, each technical module, characterized by a set of DPs corresponding to a set of FFs, exhibits commonality through clustering similar DP instances by chunks (Ulrich and Eppinger 1995). Instead of measuring similarity among CA instances, physical instances (instances of CAs for a physical module type) are grouped mostly

TABLE 1 A Comparison of Modularity and Commonality

Issues	Modularity	Commonality
Focused Objects	Type (Class)	Instances (Members)
Characteristic of Measure	Interaction	Similarity
Analysis Method	Decomposition	Clustering
Product Differentiation	Product Structure	Product Variants
Integration/Relation	Class-Member Relationship	

according to appropriate categorization of engineering costs derived from assessing existing capabilities and estimated volume, that is, economic evaluation.

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

2.1.2. Product Variety

Product variety is defined as the diversity of products that a manufacturing enterprise provides to the marketplace (Ulrich 1995). Two types of variety can be observed: functional variety and technical variety. *Functional variety* is used broadly to mean any differentiation in the attributes related to a product's functionality from which the customer could derive certain benefits. On the other hand, *technical variety* refers to diverse technologies, design methods, manufacturing processes, components and/or assemblies, and so on that are necessary to achieve specific functionality of a product required by the customer. In other words, technical variety, though it may be invisible to customers, is required by engineering in order to accommodate certain customer-perceived functional variety. Technical variety can be further categorized into product variety and process variety. The technical variety of products is embodied in different components/modules/parameters, variations of structural relationships, and alternative configuration mechanisms, whilst process variety involves those changes related to process planning and production scheduling, such as various routings, fixtures/setups, and workstations. While functional variety is mostly related to customer satisfaction from the marketing/sales perspective, technical variety usually involves manufacturability and costs from the engineering perspective.

Even though these two types of variety have some correlation in product development, they result in two different variety design strategies. Since 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 variety and manifests itself through vast research in the business community, such as product line structuring (Page and Rosenbaum 1987; Sanderson and Uzumeri 1995), equilibrium pricing (Choi and DeSarbo 1994), and product positioning (Choi et al. 1990). In contrast, design for "technical" variety tries to reduce technical variety so as to gain cost advantages. Under this category, "research" includes variety reduction program (Suzue and Kohdate 1990), design for variety (Ishii et al. 1995a; Martin and Ishii 1996, 1997), design for postponement (Feitzinger and Lee 1997), design for technology life cycle (Ishii et al. 1995b), function sharing (Ulrich and Seering 1990), and design for modularity (Erixon 1996).

Figure 3 illustrates the implications of variety and its impact on variety fulfillment. While exploring functional variety in the functional view through customer requirement analysis, product

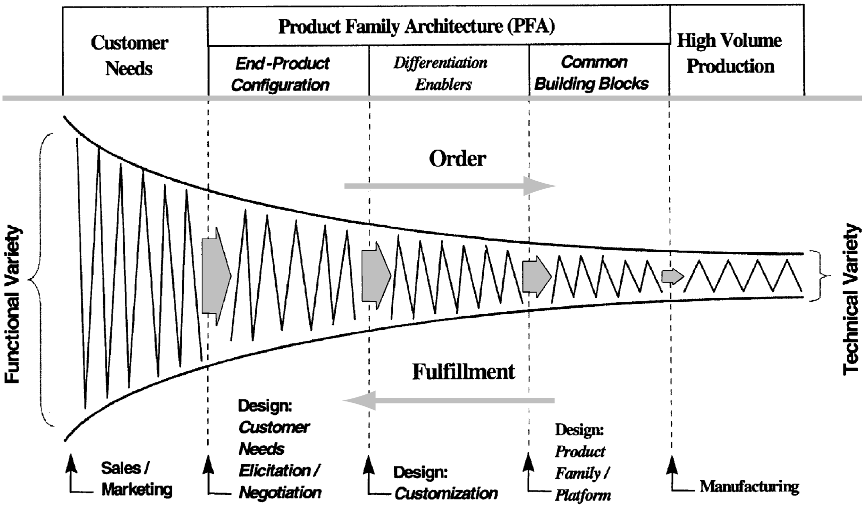

Figure 3 Variety Leverage: Handling Variety for Mass Customization.

family development should try to reduce technical variety in the design and process views by systematic planning of modularity and commonality so as to facilitate plugging in modules that deliver specific functionality, reusing proven designs and reducing design changes and process variations.

2.2. Product Family Architecture

As the backdrop of product families, a well-planned product family architecture (PFA)—the conceptual structure and overall logical organization of generating a family of products—provides a generic umbrella for capturing and utilizing commonality, within which each new product instantiated and extends so as to anchor future designs to a common product line structure. The rationale of such a PFA resides not only in unburdening the knowledge base from keeping variant forms of the same solution, but also in modeling the design process of a class of products that can widely variegate designs based on individual customization requirements within a coherent framework.

Figure 4 illustrates the principle of PFA with respect to product family development for mass customization. From the sales point of view, customers are characterized by combinations of functional features, $\{f\}$, and associated feature values, $\{f^*\}$. A product family, $\{V_1, V_2, V_3, \ldots, V_i, \ldots, V_m\}$, is designed to address the requirements of a group of customers in the market segment, $\{\text{Customer}_1, \text{Customer}_2, \text{Customer}_3, \ldots, \text{Customer}_i, \ldots, \text{Customer}_m\}$, in which customers share certain common requirements, f_0^* along with some similar and/or distinct requirements, $\{f_1^*, f_2^*, f_3^*, \ldots, f_n^*\}$. From the engineering perspective, product variants of the product family are derived from configuring common bases, $\{C\}$, and differentiation enablers, $\{E\}$, that are predefined for a product family. Configuration mechanisms determine the generative aspect of PFA. They guarantee that only both technically feasible and market-wanted product variants can be derived (Baldwin and Chung 1995).

2.2.1. *Composition of PFA*

The PFA consists of three elements: the common base, the differentiation enabler, and the configuration mechanism.

1. *Common base:* Common bases (CBs) are the shared elements among different products in a product family. These shared elements may be in the form of either common (functional) features from the customer or sales perspective or common product structures and common components from the engineering perspective. Common features indicate the similarity of

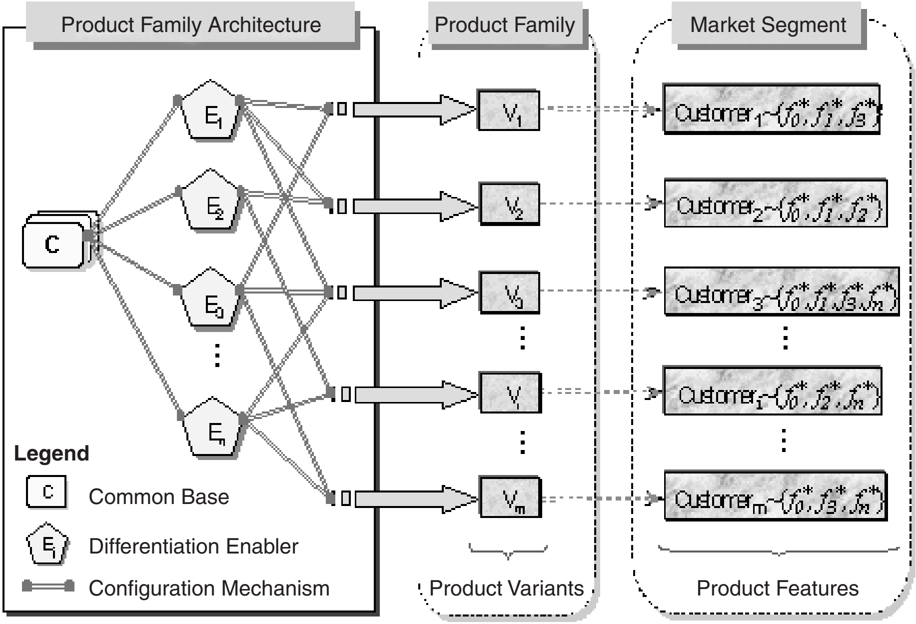

Figure 4 PFA and Its Relationships with Market Segments.

customer requirements related to the market segment. Common product structures and components are determined by product technologies, manufacturing capabilities and economy of scale.

2. *Differentiation enabler:* Differentiation enablers (DEs) are basic elements making products different from one another. They are the source of variety within a product family. From the customer perspective, DEs may be in the form of optional features, accessories, or selectable feature values. In a computer, for example, while a CD drive is an optional feature (yes/no), the RAM must be one instance of a set of selectable feature values, such as 64K, 128K, and 256K bites. In the engineering view, DEs may be embodied in distinct structural relationship (structural DEs) and/or various modules with different performance (constituent DEs). Each engineering DE usually has more than one alternative applicable to product variant derivation for specific applications.
3. *Configuration mechanism:* Configuration mechanisms (CMs) define the rules and means of deriving product variants. Three types of configuration mechanisms can be identified: selection constraints, include conditions, and variety generation.

Selection constraints specify restrictions on optional features because certain combinations of options (i.e., alternative values of optional features) are not allowed or feasible or, on the contrary, are mandatory. An example of the selection constraint for a car might be: "If cylinder (feature) is 1.3 liter (option) and fuel (feature) is diesel (option), a five-speed (option) gearbox (feature) is mandatory." Selection constraints eliminate those technically infeasible or market-unwanted products from all possible combinations of the offered options (Baldwin and Chung 1995). The theoretical number of combination is the Cartesian product of possible feature values (options).

Include conditions are concerned with the determination of alternative variants for each differentiation enabler. The include condition of a variant defines the condition under which the variant should be used or not used with respect to achieving the required product characteristics. It may be in the form of a logic function with parameter values of the differentiation enabler or with its parent constituent as independent variables. For example, an office chair (a parent) consists of one supporting module (a child), which performs as a differentiation enabler. Supposed there are two variants for this supporting module: "using wheels" and "using pads." The include condition of "using wheels" is "the office chair is drivable," while the include condition of "using pads" is "the office chair is not drivable." This include condition is defined in the form of a logic function of the parent's (office chair) variable, "drivable or not." Essentially, include conditions involve the engineering definition stage of product development.

Variety generation refers to the way in which the distinctiveness of product features can be created. It focuses on the engineering realization of custom products in the form of product structures. Such variety fulfillment is related to each differentiation enabler. This chapter identifies three basic methods of variety generation (Figure 5): attaching, swapping, and scaling, in light of the rationale of modular product architecture (Ulrich 1995; Ulrich and Tung 1991). More complex variety-generation methods can be composed by employing these basic methods recursively with reference to the hierarchical decomposition of product structures.

2.2.2. Synchronization of Multiple Views

It has been a common practice for different departments in a company have different understandings of product families from their specific perspectives. Such incoherence in semantics and subsequent deployment of information represents a formidable hindrance to current engineering data management systems (EDBS) (Krause et al. 1993). It is necessary to maintain different perspectives of product family representation in a single context. In addition, variety originates from the functional domain and propagates across the entire product-development process. Therefore, the representation of product families should characterize various forms of variation at different stages of product development.

The strategy is to employ a generic, unified representation and to use its fragments for different purposes, rather than to maintain consistency among multiple representations through transformation of different product data models to standard ones. Figure 6 illustrates such a representation scheme of PFA, where functional, behavioral, and structural (noted as FBS) views are tailored for specific departments and design phases.

While corresponding to and supporting different phases of product development, the FBS view model integrates several business functions in a context-coherent framework. This is embodied by mappings between the three views (Figure 6). Various types of customer needs (customer groups) are mapped from the functional view to the behavioral view characterized by solution principles (TPs and modular structures). Such a mapping manifests design activities. The mapping between the behavioral view and the structural view reflects considerations of manufacturing and logistics, where the modular structure and technical modules in terms of TPs are realized by physical modules in terms of components and assemblies through incorporating assessments of available process capa-

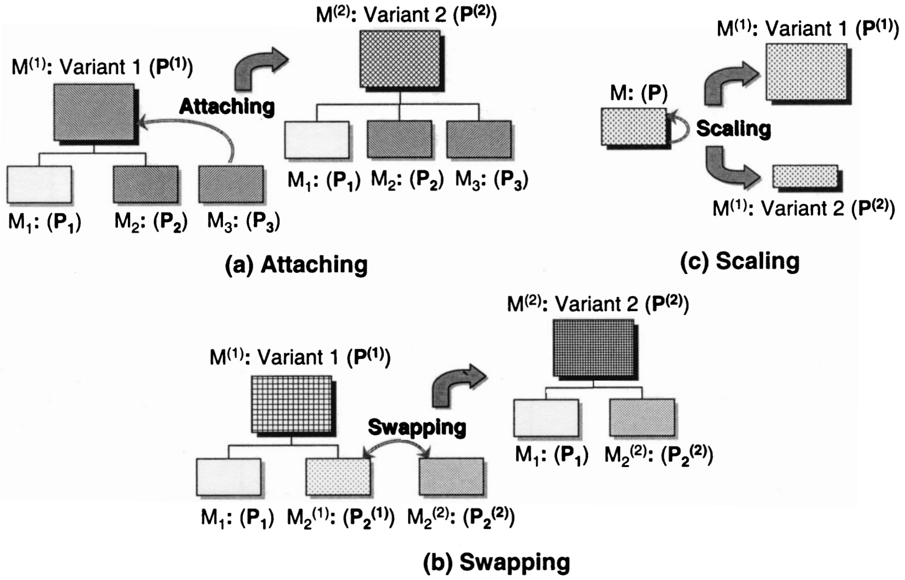

Figure 5 Basic Methods of Variety Generation.

bilities and the economy of scale. The sales and marketing functions involve mapping between the structural and functional views, where the correspondence of a physical structure to its functionality provides necessary information to assist in negotiation among the customers, marketers, and engineers, such as facilitating the request for quotation (RFQ).

2.3. Product Family Design

Under the umbrella of PFA, product family design manifests itself through the derivation processes of product variants based on PFA constructs. Figure 7 illustrates the principle of PFA-based product

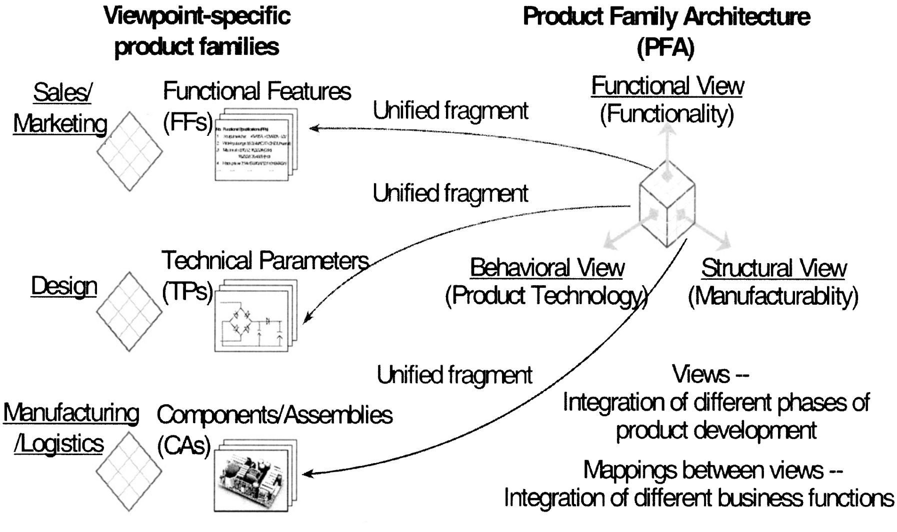

Figure 6 Representing Multiple Views of Product Family within a Single Context.

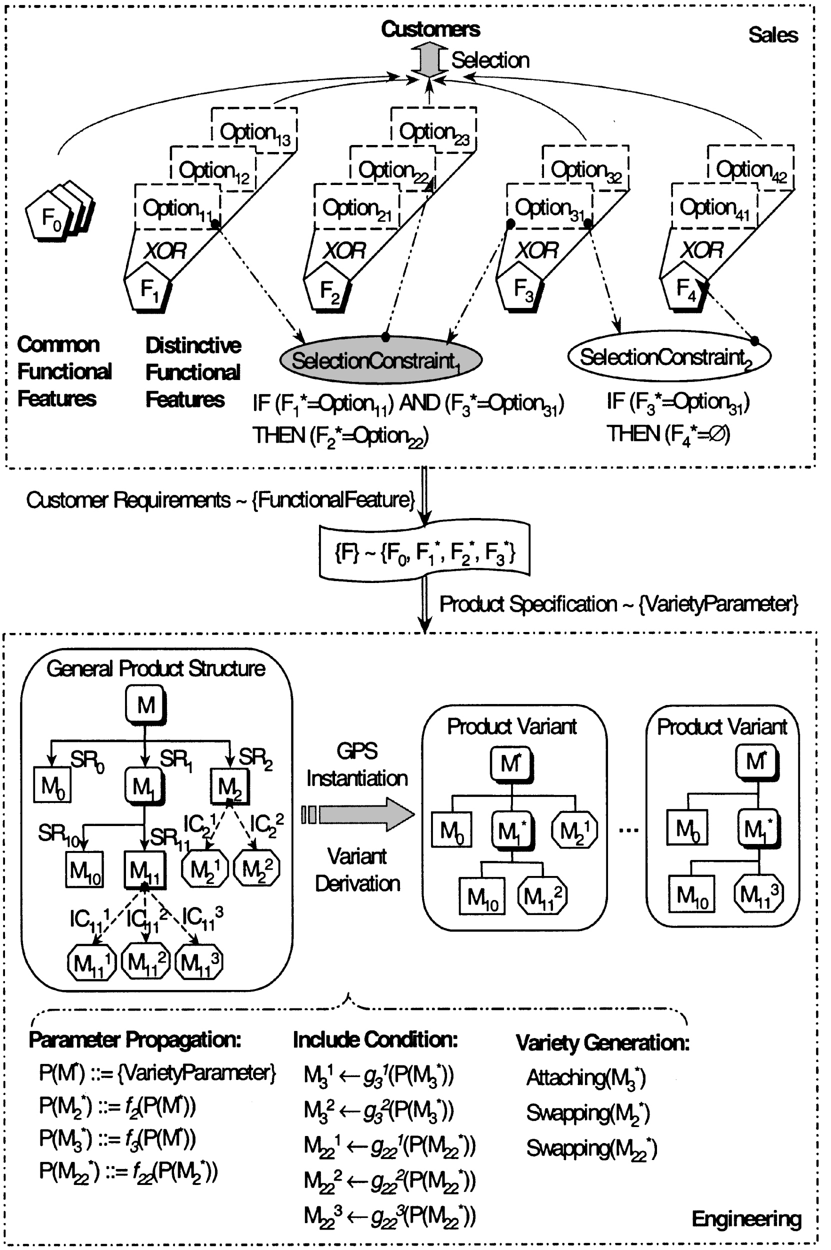

Figure 7 PFA-Based Product Family Design: Variant Derivation through GPS Instantiation.

family design. Customers make their selections among sets of options defined for certain distinctive functional features. These distinctive features are the differentiation enablers of PFA in the sales view. Selection constraints are defined for presenting customers only feasible options, that is, both technically affordable and market-wanted combinations. A set of selected distinctive features together with those common features required by all customers comprise the customer requirements of a customized product design. As shown in Figure 7, customized products are defined in the sales view in the form of functional features and their values (options), whereas in the engineering view, product family design starts with product specifications in the form of variety parameters. Within the PFA, variety parameters correspond to distinctive functional features and the values of each variety parameter correspond to the options of each functional feature.

To realize variety, a general product structure (GPS) is employed as a generic data structure of product family in the engineering view. The derivation of product variants becomes the instantiation of GPS. While the GPS characterizes a product family, each instance of GPS corresponds to a product variant of the family. Each item in the GPS (either a module or a structural relationship) is instantiated according to certain include conditions that are predefined in terms of variety parameters. Variety parameters originate from functional features specified by the customers and propagate along levels of abstraction of GPS. Variety generation methods, such as attaching, swapping, and scaling, are implemented through different instantiations of GPS items. While the GPS provides a common base for product family design, distinctive items of GPS, such as distinctive modules and structural relationships, perform as the differentiation enablers of the family. Distinctive items are embodied in different variants (instances) that are identified by associated conditions. Therefore, these include conditions and the variety generation capability constitutes configuration mechanisms of PFA in the engineering view.

3. MASS CUSTOMIZATION MANUFACTURING

Competition for mass customization manufacturing is focused on the flexibility and responsiveness in order to satisfy dynamic changes of global markets. The traditional metrics of cost and quality are still necessary conditions for companies to outpace their competitors, but they are no longer the deciding factors between winners and losers. Major trends are:

1. A major part of manufacturing will gradually shift from mass production to the manufacturing of semicustomized or customized products to meet increasingly diverse demands.
2. The "made-in-house" mindset will gradually shift to distributed locations, and various entities will team up with others to utilize special capabilities at different locations to speed up product development, reduce risk, and penetrate local markets.
3. Centralized control of various entities with different objectives, locations, and cultures is almost out of the question now. Control systems to enable effective coordination among distributed entities have become critical to modern manufacturing systems.

To achieve this, it is becoming increasingly important to develop production planning and control architectures that are modifiable, extensible, reconfigurable, adaptable, and fault tolerant. Flexible manufacturing focuses on batch production environments using multipurpose programmable work cells, automated transport, improved material handling, operation and resource scheduling, and computerized control to enhance throughput. Mass customization introduces multiple dimensions, including drastic increase of variety, multiple product types manufactured simultaneously in small batches, product mixes that change dynamically to accommodate random arrival of orders and wide spread of due dates, and throughput that is minimally affected by transient disruptions in manufacturing processes, such as breakdown of individual workstations.

3.1. Managing Variety in Production Planning

Major challenge of mass customization production planning results from the increase of variety. The consequence of variety may manifest itself through several ramifications, including increasing costs due to the exponential growth of complexity, inhibiting benefits from economy of scale, and exacerbating difficulties in coordinating product life cycles. Facing such a variety dilemma, many companies try to satisfy demands from their customers through engineering-to-order, produce-to-order, or assembly-to-order production systems (Erens and Hegge 1994).

At the back end of product realization, especially at the component level and on the fabrication aspect, today we have both flexibility and agility provided by advanced manufacturing machinery such as CNC machines. These facilities accommodate technical variety originating from diverse needs of customers. However, at the front end, from customer needs to product engineering and production planning, managing variety is still very ad hoc. For example, production control information systems, such as MRPII (manufacturing resource planning) and ERP (enterprise resource planning), are falling behind even though they are important ingredients in production management (Erens et al. 1994). The difficulties lie in the necessity to specify all the possible variants of each product and in the fact that current production management systems are often designed to support a production that is based on a limited number of product variants (van Veen 1992).

The traditional approach to variant handling is to treat every variant as a separate product by specifying a unique BOM for each variant. This works with a low number of variants, but not when customers are granted a high degree of freedom in specifying products. The problem is that a large number of BOM structures will occur in mass customization production, in which a wide range of combinations of product features may result in millions of variants for a single product. Design and maintenance of such a large number of complex data structures are difficult, if not impossible. To overcome these limitations, a generic BOM (GBOM) concept has been developed (Hegge and Wortmann 1991; van Veen 1992). The GBOM provides a means of describing, with a limited amount of data, a large number of variants within a product family, while leaving the product structure unimpaired. Underlying the GBOM is a generic variety structure for characterizing variety, as schematically illustrated in Figure 8. This structure has three aspects:

1. *Product structure:* All product variants of a family share a common structure, which can be described as a hierarchy containing constituent items (I_i) at different levels of abstraction, where $\{I_i\}$ can be either abstract or physical entities. Such a breakdown structure (AND tree) of $\{I_i\}$ reveals the topology for end-product configuration (Suh 1997). Different sets of I_i and their interrelationships (in the form of a decomposition hierarchy) distinguish different common product structures and thus different product families.
2. *Variety parameters:* Usually there is a set of attributes, A, associated with each I_i. Among them, some variables are relevant to variety and thus are defined as variety parameters, $\{P_j\} \subset A$. Like attribute variables, parameters can be inherited by child node(s) from a parent node. Different instances of a particular P_j, e.g., $\{V_k\}$, embody the diversity resembled by, and perceived from, product variants.

   Two types of class-member relationships can be observed between $\{P_j\}$ and $\{V_k\}$. A leaf P_j (e.g., *P32*) indicates a binary-type instantiation, meaning whether *I32* is included in *I3* (*V32* = 1), or not (*V32* = 0). On the other hand, a node P_j (e.g., *P2*) indicates a selective type instantiation, that is, *I2* has several variants in terms of values of *P2*, i.e., *V2* ~ {*V2_1*, *V2_2*}.
3. *Configuration constraints:* Two types of constraint can be identified. Within a particular view of product families, such as the functional, behavioral, or physical view, restrictions on the

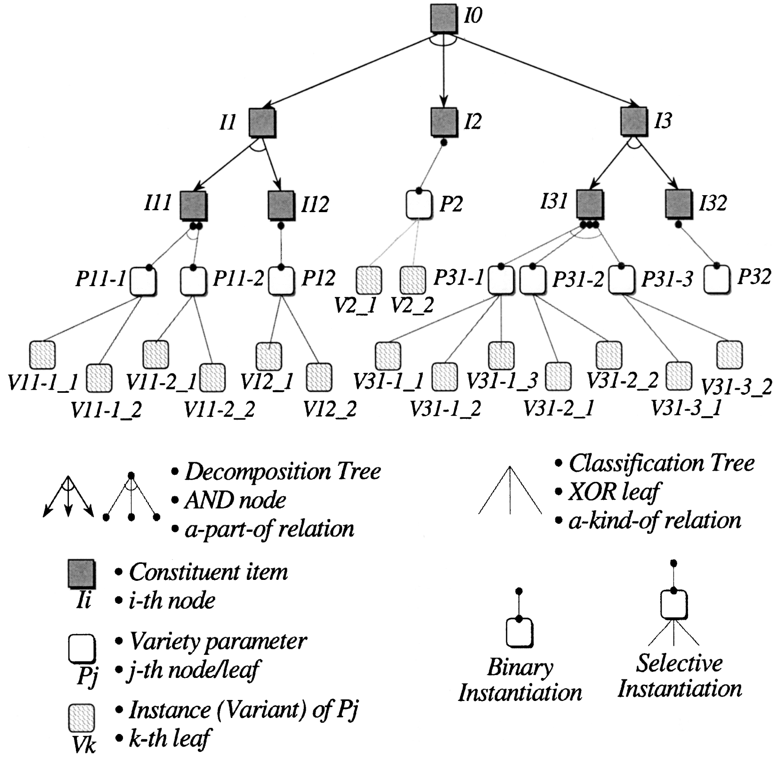

Figure 8 A Generic Structure for Characterizing Variety.

combination of parameter values, $\{V_k\}$, are categorized as Type I constraints. For example, *V11-1_1* and *V31-3_2* are incompatible, that is, only one of them can be selected for a product variant, indicating an exclusive all (XOR) relationship. The mapping relationships of items and their variety parameters across the functional, behavioral, and structural views are referred to as Type II constraints. This type of constraint deals mostly with configuration design knowledge. Usually they are described as rules instead of being graphically depicted in a generic structure. While the functional and behavioral views of product families are usually associated with product family design, the major concern of managing variety in production is Type I constraints which mostly involves the structural view.

Table 2 illustrates the above generic variety structure using a souvenir clock example. As far as variant handling is concerned, the rationale of the generic variety structure lies in the recognition of the origin and subsequent propagation of variety. Three levels of variation have been indicated, that is, at the structure, variety parameter, and instance levels. Different variation levels have different variety implications. To understand the "generic" concept underlying such a variety representation, two fundamental issues need to be highlighted:

1. *Generic item:* A generic item represents a set of similar items (called variants) of the same type (a family). The item may be an end product, a subassembly, an intermediate part, or a component part (van Veen, 1992). It may also be a goes-into-relationship or an operation. For example, a red front plate (I_1^*), a blue front plate (I_2^*) and a transparent front plate (I_3^*) are three individual variants, whereas a generic item, *I*, represents such a set of variants (a family of front plates), that is $\boldsymbol{I} \sim \{I_1^*, I_2^*, I_3^*\}$. However, these variants are similar in that they share a common structure (e.g., BOM structure) in configuring desk clocks.
2. *Indirect identification:* Instead of using part numbers (referred to as direct identification), the identification of individual variants from a generic item (within a family) is based on variety parameters and their instances (a list if parameter values). Such identification is called indirect identification (Hegge and Wortmann. 1991). In the above example, a variety parameter, color, and its value list, , can be used for an indirect identification of a particular variant, i.e., $I_1^* \sim$

TABLE 2 The Generic Variety Structure for Souvenir Clocks

Structural Items $\{I_i\}$	Variety Parameter $\{P_j\}$	Variety Instance $\{V_k\}$
..3/Hands	Setting Type	Two-hand Setting, Three-hand Setting
	Color	White, Grey, etc.
	Size	Large, Medium, Small
..3/Dial	Pattern	Logo, Mosic, Scenery, Customized Photo, etc.
	Size	Large, Medium, Small
...4/Transmission	Alarm	Yes, No
...4/Core	Alarm	Yes, No
..3/Base	Shape	Round, Rectangular, Hexagonal
	Material	Acrylic, Aluminum, etc.
	Color	Transparent, Red, etc.
..3/Front Plate	Shape	Rectangular, Round, Rhombus
	Material	Acrylic, Aluminum, etc.
	Color	Transparent, Red, etc.
..1/Label Sticker	Pattern	HKUST, Signature, etc.
..1/Paper Box	Type	Ordinary, Deluxe, etc.

Constraint #	Constraint Fields	Constraint Type
1	Hands.Size Dial.Size	Size Compatible
2	Transmission.Alarm Core.Alarm	Type Compatible
3	Base.Material FrontPlate.Material	Material Compatible
4	Base.Color FrontPlate.Color	Color Compatible

$\{\boldsymbol{I}|\text{color} = \text{“red”}\}$ and $I_3^* \sim \{\boldsymbol{I}|\text{color} = \text{“transparent”}\}$. On the other hand, the identification of product family “front plate” is $\boldsymbol{I}$.

3.2. Coordination in Manufacturing Resource Allocation

Mass customization manufacturing is characterized by shortened product life cycle with high-mixed and low-volume products in a rapidly changing environment. In customer-oriented plants, orders consisting of a few parts, or even one part, will be transferred directly from vendors to producers, who must respond quickly to meet short due dates. In contrast to mass production, where the manufacturer tells consumers what they can buy, mass customization is driven by customers telling the manufacturer what to manufacture. As a result, it is difficult to use traditional finite capacity scheduling tools to support the new style of manufacturing. Challenges of manufacturing resource allocation for mass customization include:

1. The number of product variety flowing through the manufacturing system is approaching an astronomical scale.
2. Production forecasting for each line item and its patterns is not often available.
3. Systems must be capable of rapid response to market fluctuation.
4. The system should be easy for reconfiguration—ideally, one set of codes employed across different agents.
5. The addition and removal of resources or jobs can be done with little change of scheduling systems.

Extensive research on coordination of resource allocation has been published in connection with scenarios of multiple resource providers and consumers. In the research, existence of demand patterns is the prerequisite for deciding which algorithm is applicable. The selection of a certain algorithm is often left to empirical judgment, which does not alleviate difficulties in balancing utilization and level of services (e.g., meeting due dates).

As early as 1985, Hatvany (1985) pointed out that the rigidity of traditional hierarchical structures limited the dynamic performance of systems. He suggested a heterachical system, which is described as the fragmentation of a system into small, completely autonomous units. Each unit pursues its own goals according to common sets of laws, and thus the system possesses high modularity, modifiability, and extendibility. Following this idea, agent-based manufacturing (Sikora and Shaw 1997) and holonic manufacturing (Gou et al. 1994), in which all components are represented as different agents and holons, respectively, are proposed to improve the dynamics of operational organizations.

From traditional manufacturing perspectives, mass customization seems chaotic due to its large variety, small batch sizes, random arrival orders, and wide span of due dates. It is manageable, however, owing to some favorable traits of modern manufacturing systems, such as inherent flexibility in resources (e.g., increasing use of machining centers and flexible assembly workstations) and similarities among tools, production plans, and product designs. The challenge is thus how to encode these characteristics into self-coordinating agents so that the invisible hand, in the sense of Adam Smith’s market mechanism (Clearwater 1996), will function effectively.

Market-like mechanisms have been considered as an appealing approach for dealing with the coordination of resource allocation among multiple providers and consumers of resources in a distributed system (Baker 1991; Malone et al. 1988; Markus and Monostori 1996). Research on such a distributed manufacturing resource-allocation problem can be classified into four categories: the bidding/auction approach (Shaw 1988; Upton and Barash 1991), negotiation approach (Lin and Solberg 1992), cooperative approach (Burke and Prosser 1991) and pricing approach (Markus and Monostori 1996).

Major considerations of scheduling for resource allocation include:

1. Decompose large, complex scheduling problems into smaller, disjointed allocation problems.
2. Decentralize resource access, allocation, and control mechanisms.
3. Design a reliable, fault-tolerant, and robust allocation mechanism.
4. Design scalable architectures for resource access in a complex system and provide a plug-and-play resource environment such that resource providers and consumers can enter or depart from the market freely.
5. Provide guarantees to customers and applications on performance criteria.

In this regard, the agent-based, market-like mechanism suggests itself as a means of decentralized, scalable, and robust coordination for resource allocation in a dynamic environment (Tseng et al. 1997). In such a collaborative scheduling system, each workstation is considered as an autonomous agent seeking the best return. The individual work order is considered as a job agent that vies for

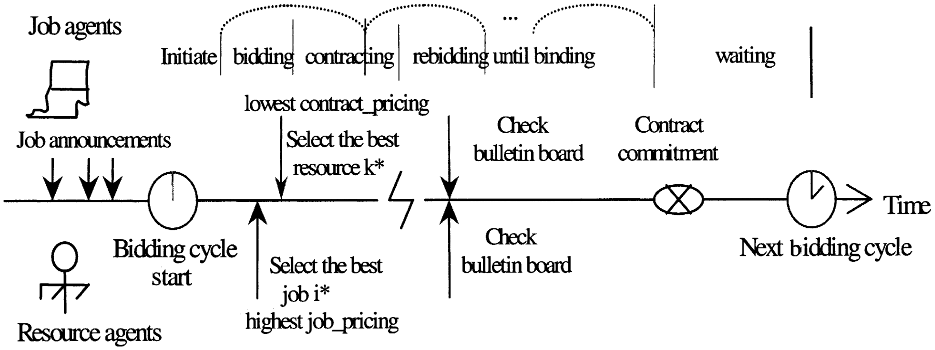

Figure 9 A Market Structure for Collaborative Scheduling.

the lowest cost for resource consumption. System scheduling and control are integrated as an auction-based bidding process with a price mechanism that rewards product similarity and response to customer needs. A typical market model consists of agents, a bulletin board, a market system clock, the market operating protocol, the bidding mechanism, pricing policy, and the commitment mechanism. Figure 9 illustrates how the market operating protocol defines the rules for synchronization among agents.

The satisfaction of multiple criteria, such as costs and responsiveness, cannot be achieved using solely a set of dispatching rules. A price mechanism should be constructed to serve as an invisible hand to guide the coordination in balancing diverse requirements and maximizing performance in a dynamic environment. It is based on market-oriented programming for distributed computation (Adelsberger and Conen 1995). The economic perspective on decentralized decision making has several advantages. It overcomes the narrow view of dispatching rules, responds to current market needs, uses maximal net present value as the objective, and coordinates agents' activities with minimal communication. In collaborative scheduling, objectives of the job agent are transformed into a set of evaluation functions. The weights of the functions can be adjusted dynamically on basis of system states and external conditions. Resource agents adjust the charging prices based on their capability and utilization and the state of current system. Mutual selection and mutual agreement are made through two-way communication. Figure 10 depicts the market price mechanism. In the market model, the job agents change routings (i.e., select different resource agents), and adjust Job_Price as a pricing tool to balance the cost of resources and schedule exposure. Resource agents adjust their prices according to market demands on their capability and optimal utilization and returns. For example, a powerful machine may attract many job agents, and thus the queue will build up and

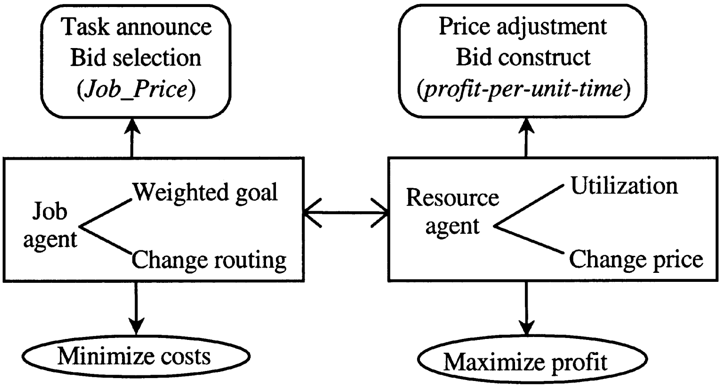

Figure 10 The Price Mechanism of a Market Model.

waiting time will increase. When a resource agent increases its price, the objective of bidding job will decrease, thus driving jobs to other resources and diminishing the demand for this resource.

Specifically, the price mechanism can be expressed as follows:

1. The job agent calculates the price to be paid for the *i* operation:

$$\text{Job\_price} = \text{Basic\_price} + \text{Penalty\_price} \tag{1}$$

   where the Penalty_price reflects the due date factor:

$$\text{Penalty\_price} = \text{penalty} \times e^{-(d_i - c_i)} \tag{2}$$

   where d_i represents the due date of the operation i and c_i represents the completion time of the operation i.

2. The resource agent gets the Job_price and then starts to rank the job according to profit per unit time:

$$\text{Profit/time} = (\text{Job\_price} - \text{PFAindex} \times s - \text{Opportunity\_cost})/tp \tag{3}$$

   where s represents the setup cost, tp denotes the processing time of the operation, and PFAindex represents the product family consideration in setting up the manufacturing system. For instance, we can let PFAindex $= 0$, if two consecutive jobs, i and j, are in the same product family, and hence the setup charge can be eliminated in the following job. Otherwise, PFAindex $= 1$. The Opportunity_cost in Eq. (3) represents the cost of losing particular slack for other job agents due to the assignment of resource for one job agent's operation i, as expressed below:

$$\text{Opportunity\_cost} = \sum_j e^{-c(\min(0,t_{sj}))}\,(e^{c\delta t_{sj}} - 1) \tag{4}$$

   where $t_{sj} = t_{dj} - t - w_j$, t_{dj} represents the due date of the corresponding job, t represents the current time (absolute time), w_j represents the remaining work content of the job, and c is a system opportunity cost parameter, setting to 0.01. In Eq. (4), δt_{sj} represents the critical loss of slack of operation j due to the scheduling of the operation i before j, as depicted below:

$$\delta t_{sj} = \begin{cases} tp_i, & t_{sj} \le 0 \\ 0 & tp_i \ge t_{sj} \\ tp_i - t_{sj}, & t_{sj} \ge tp_i \end{cases} \tag{5}$$

   Meanwhile, the resource agent changes its resource price p_i:

$$p_i = q \sum_k \text{Job\_price}_k \tag{6}$$

   where q is a normalized constant.

3. The job agent, in a period of time, collects all bids and responds to its task announcement and selects the resource agent with minimal Actual_cost to confirm the contract:

$$\text{Actual\_cost} = p_i \times tp_i + \max((c_i - d_i),0) \times \text{penalty} \tag{7}$$

Based on the above formulations, the collaborative control can be modeled as a message-based simulation, as shown in Figure 11. The control process is driven by an event and/or an abnormal event, such as machine breakdown or a new due date. All events can be represented as messages.

3.3. High-Variety Shop-Floor Control

Mass customization manufacturing motivates a new generation of shop-floor control systems that can dynamically respond to customer orders and unanticipated changes in the production environment. The requirements of the new control systems include reconfigurability, decomposability, and scalability to achieve make-to-order with very short response time. A systematic approach has been developed to design control system by leveraging recent progresses in computing and communication hardware and software, including new software engineering methods and control technologies, such as smart sensors and actuators, open architectures, and fast and reliable networks (Schreyer and Tseng

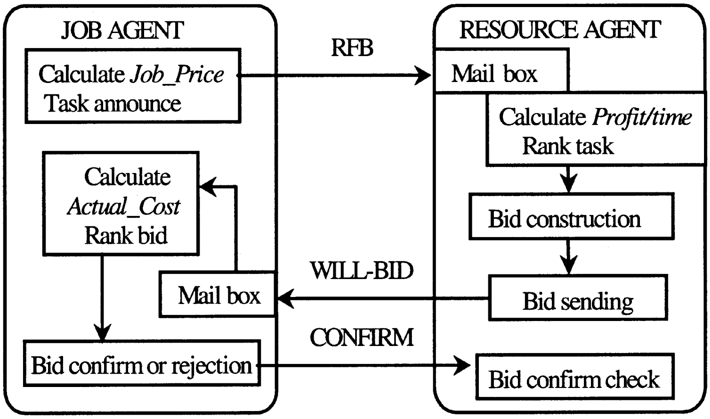

Figure 11 Message-Based Bidding and Dynamic Control.

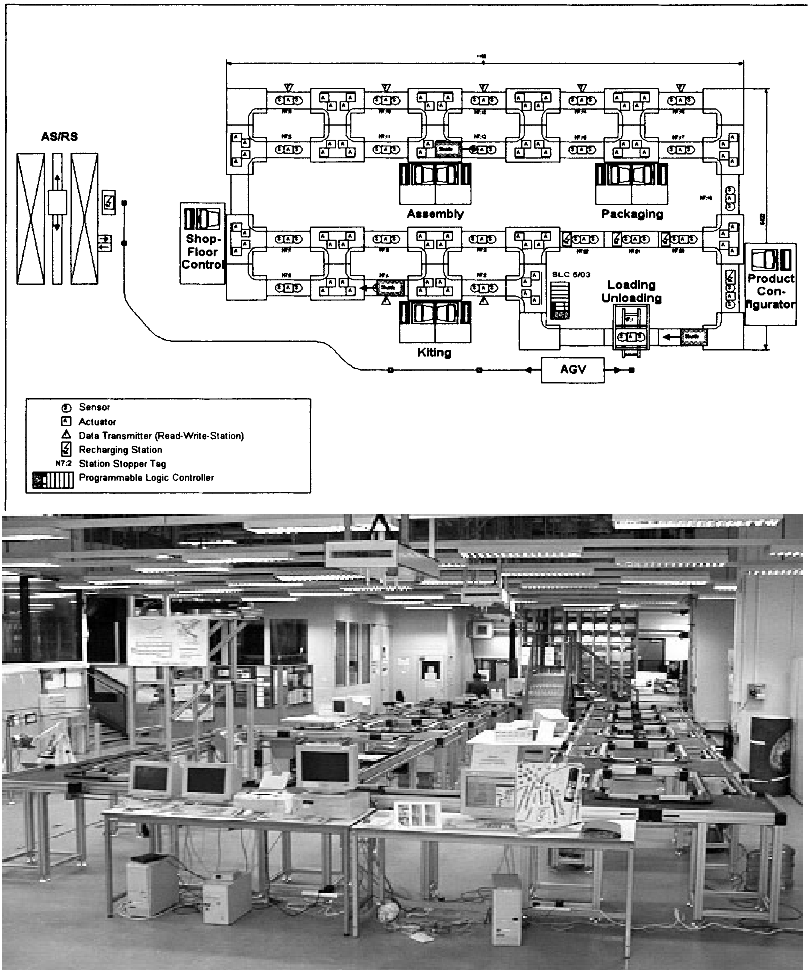

Figure 12 Example of Installation of Mass Customization Manufacturing System at the Hong Kong University of Science and Technology.

1998). Figure 12 illustrates an actual example of installation of a mass customization manufacturing system in the Hong Kong University of Science and Technology.

4. SALES AND MARKETING FOR MASS CUSTOMIZATION

In the majority of industries and sectors, customer satisfaction is a powerful factor in the success of products and services. In the era of mass production, customers were willing to constrain their choices to whatever was available, as long as the price was right. However, customers today are liberated and better informed. This leads them to be choosy about their purchases and less willing to compromise with what is on the shelf. Meeting customer requirements requires full understanding of customers' values and preferences. In addition, it is important that customers know what the company can offer as well as their possible options and the consequences of their choices, such as cost and schedule implications.

4.1. Design by Customers

The setup time and its resulting economy of scale have been widely accepted as the foundation for the mass production economy, where batch size and lead time are important instruments. Consequently, the popular business model of today's firms is design *for* customers. Companies design and then produce goods for customers through conforming a set of specifications that anticipates customer's requirements. Often the forecasting of end users' requirements is developed by the marketing department. It is usually carried out through aggregating the potential needs of customers with the consideration of market direction and technology trends. Given the complexities of modern products, the dynamic changes in customers' needs, and the competitive environment in which most businesses have to operate, anticipating potential customers' needs can be very difficult. Chances are that forecasting will deviate from the reality by a high margin. Three major economic deficiencies are often encountered.

Type A is the possibility of producing something that no customers want. The waste is presented in the form of inventory, obsolescence, or scrap. Although a significant amount of research and development has been conducted on improving the forecast accuracy, inventory policy, increased product offerings, shortened time-to-market, and supply chain management, avoiding the possibility of producing products that no customer want is still a remote, if not impossible, goal.

Type B waste comes from not being able to provide what customers need when they are ready to purchase. It often presents itself in the form of shortage or missing opportunity. The costs of retail stores, marketing promotion, and other sales expenditures on top of the goods themselves will disappoint the customers who are ready to purchase. The cost of missing opportunities can be as significant as the first type.

Type C deficiency results from customers making compromises between their real requirements and existing SKUs (stock keeping units), that is, what is available on the shelf or in the catalogue. Although these compromises are usually not explicit and are difficult to capture, they lead to customer dissatisfaction, reduce willingness to make future purchases, and erode the competitiveness of a company.

To minimize the effect of these deficiencies, one approach is to revise the overall systems design of a manufacturing enterprise. Particularly with the growing flexibility in production equipment, manufacturing information systems and workforce, the constraints of setup cost and lead time in manufacturing have been drastically reduced. The interface between customers and product realization can be reexamined to ensure that total manufacturing systems produce what the customers want and customers are able to get what the systems can produce within budget and schedule. Furthermore, with the growing trends of cultural diversity and self-expression, more and more customers are willing to pay more for products that enhance their individual sizes, tastes, styles, needs, comfort, or expression (Pine 1993).

With the rapid growth of Internet usage and e-commerce comes an unprecedented opportunity for manufacturing enterprise to connect directly customers scattered around the world. In addition, through the Internet and business-to-business e-commerce, manufacturing enterprise can now acquire access to the most economical production capabilities on a global basis. Such connectivity provides the necessary condition for customers to become connected to the company. However, by itself it will not enhance effectiveness.

In the last decade, concurrent engineering brought together design and manufacturing, which has dramatically reduced the product development life cycle and hence improved quality and increased productivity and competitiveness. Therefore, design *by* customers has emerged as a new paradigm to further extend concurrent engineering by extending connectivity with customers and suppliers (Tseng and Du 1998). The company will be able to take a proactive role in helping customers define needs and negotiate their explicit and implicit requirements. Essentially, it brings the voice of customers into design and manufacturing, linking customer requirements with the company's capabilities and extending the philosophy of concurrent engineering to sales and marketing as part of an integrated product life cycle. Table 3 summarizes the comparison of these two principles for customer-focused product realization.

The rationale of design by customers can be demonstrated by the commonly accepted value chain concept (Porter 1986). The best match of customer needs and company capability requires several technical challenges:

1. Customers must readily understand the capability of a company without being a design engineer or a member in the product-development team.
2. Company must interpret the needs of customers accurately and suggest alternatives that are closest to the needs.
3. Customers must make informed choices with sufficient information about alternatives.
4. Company must have the ability to fulfill needs and get feedback.

To tackle these challenges, it is necessary that customers and the company share a context-coherent framework. Product configuration has been commonly used as a viable approach, primarily because it enables both sides to share the same design domain. Based on the product configuration approach, the value chain, which includes the customer interface, can be divided into four stages:

1. *Formation:* Presenting the capability that a company can offer in the form of product families and product family structure.
2. *Selection:* Finding customers' needs and then matching the set of needs by configuring the components and subassemblies within the constraints set by customers.
3. *Fulfillment:* Includes logistics, manufacturing and distribution so that customer' needs can be satisfied within the cost and time frame specified.
4. *Improvement:* Customers' preferences, choices, and unmet expressed interests are important inputs for mapping out the future improvement plan.

Formation and selection are new dimensions of design for customer. They are explained further below.

4.2. Helping Customers Making Informed Choices: Conjoint Analysis

Design *by* customers assumes customers are able to spell out what they want with clarity. Unfortunately, this is often not the case. To begin with, customers may not be able to know what is possible. Then the system needs to pull the explicit and implicit needs from customers. Conjoint analysis is a set of methods in marketing research originally designed to measure consumer preferences by assessing the buyers' multiattribute utility functions (Green and Krieger, 1989; IntelliQuest 1990). It assumes that a product could be described as vectors of M attributes, $Z_1, Z_2, \ldots, Z_M$. Each attribute can include several discrete levels. Attribute Z_m can be at any one of the L_m levels, $Z_{m1}, Z_{m2}, \ldots, Z_{m,Lm}$, $m \in [1, M]$. A utility functions is defined as (McCullagh and Nelder 1989):

$$U_r = \sum_{m=1}^{M} W_m \left(\sum_{l=1}^{L_m} d_{ml} X_{rml} \right) = \sum_{m=1}^{M} \sum_{l=1}^{L_m} U_{ml} X_{rml} \tag{8}$$

$$U_{ml} = W_m * d_{ml} \tag{9}$$

where U_r = customer's utility for profile r, $r \in [1, R]$
W_m = importance of attribute Z_m for the customer
d_{rml} = desirability for l^{th} level of attribute m, $l \in [1, L_m]$, $m \in [1, M]$
U_{ml} = utility of attribute m's l^{th} level

TABLE 3 A Comparison of Design for Customers and Design by Customers

Principle	Design for Customers	Design by Customers
Manufacturing Practice	Mass production	Mass customization
Design	Anticipate what customers would buy	Create platforms and capabilities
Manufacturing	Build to forecast	Build to order
Sales	Promote what is available	Assist customers to discover what can be done and balance their needs

In the above formulation, X_{rml} is a dummy variable indicating whether or not the particular level of an attribute is selected, as expressed by:

$$X_{rml} = \begin{cases} 1 & \text{if attribute } m \text{ is on } l^{\text{th}} \text{ level;} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Usually, a large number of attributes, discrete levels, and their preference indices is required to define the preferred products through customer interaction, and thus the process may become overwhelming and impractical. There are several approaches to overcoming this problem. Green et al. (1991) and IntelliQuest (1990) have proposed adaptive conjoint analysis to explore customers' utility with iterations. Customers are asked to rate the relative importance of attributes and refine the tradeoffs among attributes in an interactive setting through comparing a group of testing profiles. Other approaches, such as Kano diagram and analytic hierarchy process (AHP), can also be applied to refine the utility value (Urban and Hauser 1993).

With the utility function, U_{ml}, customers can find the relative contribution of each attribute to their wants and thus make necessary tradeoffs. Customers can finalize their design specifications by maximizing their own personal value for the unit price they are spending.

4.3. Customer Decision-Making Process

Design by customers allows customers to directly express their own requirements and carry out the mapping to the physical domain. It by no means gives customers free hand to design whatever they want in a vacuum. Instead, it guides customers in navigating through the capabilities of a firm and defining the best alternative that can meet the cost, schedule, and functional requirements of the customers. Figure 13 illustrates the process of design by customers based on a PFA platform. In the figure, arrows represent data flows, ovals represent processes, and variables in uppercase without subscript represent a set of relevant variables. This process consists of two phases: the front-end customer interaction for analyzing and matching customer needs, and the back-end supporting process for improving the compatibility of customer needs and corporate capabilities. There are two actors in the scenario: the customers and the system supported by the PFA.

4.3.1. Phase I: Customer Needs Acquisition

1. *Capability presentation:* In order to make informed decisions, customers are first informed of the capabilities of the firm, which is in the form of the spectrum of product offerings, product attributes, and their possible levels. By organizing these capabilities, the PFA provides a systematic protocol for customers to explore design options.
2. *Self-explication:* Customers are then asked to prioritize desired attributes for their requirements according to their concern about the difference. Customers must assess the value they attach to each attribute and then specify their degree of relative preference between the most desirable and the least desirable levels. The results of this assessment are a set of W_m reflecting the relative importance of each attribute.
3. Utility exploration: Based on W_m, the next task is to find a set of $d_{rml}^{(0)}$ that reflect the desirability of attribute levels. Response surface can be applied here to create a set of testing profiles to search for the value of desirability of each selected level. The AHP can be used to estimate $d_{rml}^{(0)}$. Substituting W_m and $d_{rml}^{(0)}$ in Eq. (9), the utility of each attribute level can be derived.

4.3.2. Phase II: Product Design

1. *Preliminary design:* With $d_{rml}^{(0)}$ and W_m, $U_{ml}^{(0)}$ can be calculated with Eq. (8). A base product (BP) can be determined in accordance with a utility value close to $U_{ml}^{(0)}$. Base product selection can be further fine-tuned through iterative refinement of U_{ml}.
2. *Customization:* Customers can modify the attributes from Z to $Z + \Delta Z$ through the customization process of adding building blocks. Z will be adjusted, and the utility will be recalculated, until the customer gets a satisfactory solution.
3. *Documentation:* After it is confirmed by the customers, the design can be delivered. The results include refined Z and ΔZ and customized BP and ΔBP. These will be documented for the continuous evolution of PFA. Over time, the PFA can be updated so that prospective customers can be better served. This includes changes not only in the offerings of product families but also in production capabilities so that the capabilities of a firm can be better focused to the needs of its customers.

In practice, customers may found this systematic selection process too cumbersome and time consuming. Research in the area of customer decision-making process is still undergoing.

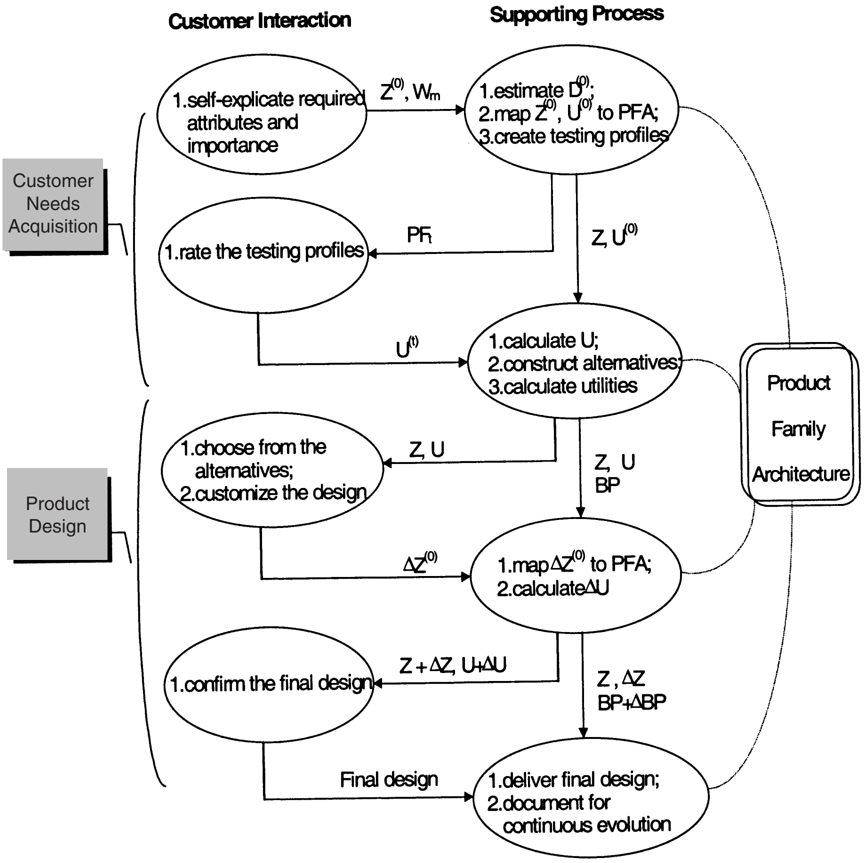

Figure 13 The Process of Customer Decision Making.

4.4. One-to-One Marketing

With the rapid transmission of mass media, globalization, and diverse customer bases, the market is no longer homogeneous and stable. Instead, many segmented markets now coexist simultaneously and experience constant changes. Customers cast their votes through purchasing to express their preferences on products. With the fierce competition, customers can easily switch from one company to another. In addition, they become less loyal to a particular brand. Because a certain portion of customers may bring more value-added to the business than the average customers, it is imperative to keep customer loyalty by putting customers at the center point of business. Such a concept has been studied by many researchers (e.g., Greyser 1997) Peppers and Rogers (1997, p. 22) state: “The 1:1 enterprise practices 1:1 marketing by tracking customers individually, interacting with them, and integrating the feedback from each customer into its behavior towards that customer.”

With the growing popularity of e-commerce, customers can directly interact with product and service providers on a real-time basis. With the help of system support, each individual customer can specify his or her needs and make informed choices. In the meantime, the providers can directly conduct market research with more precise grasp of customer profiles. This will replace old marketing models (Greyser 1997). At the beginning, the concern is the capability of manufacturers to make products—that is, it is production oriented. Then the focus shifts towards the capability to sell products that have already been made—that is, it is sales oriented. Later on, the theme is customers’ preferences and how to accommodate these preferences with respect to company capabilities—that is, it is marketing oriented. With the paradigm shift towards mass customization, manufacturers aim at providing best values to meet customers’ individual needs within a short period. The closed-loop interaction between clients and providers on a one-to-one basis will increase the efficiency of matching buying and selling.

Furthermore, the advent of one-to-one marketing transcends geographical and national boundaries. The profile of customers' individual data can be accessed from anywhere, and in turn the company can serve the customers from anywhere at any time. Nonetheless, it also creates a borderless global market that leads to global competition. To be able to sustain, companies are putting more attention on one-to-one marketing.

5. MASS CUSTOMIZATION AND E-COMMERCE

The Internet is becoming a pervasive communication infrastructure connecting a growing number of users in corporations and institutions worldwide and hence providing immense business opportunities for manufacturing enterprises. The Internet has shown its capability to connect customers, suppliers, producers, logistics providers, and almost every stage in the manufacturing value chain. Leading companies have already started to reengineer their key processes, such as new product development and fulfillment, to best utilize the high speed and low cost of the Internet. Impressive results have been reported with significant reduction in lead time, customer value enhancements, and customer satisfaction improvement. Some even predict that a new industrial revolution has already quietly started, geared towards e-commerce-enabled mass customization (*Economist* 2000; Helander and Jiao 2000).

In essence, mass customization attempts to bring customers and company capabilities closer together. With the Internet, customers and providers in different stages of production can be connected at multiple levels of the Web. How this new capability will be utilized is still at a very early stage. For examples, customers can be better informed about important features and the related costs and limitations. Customers can then make educated choices in a better way. In the meantime, through these interactions the company will then be able to acquire information about customers' needs and preferences and can consequently build up its capabilities in response to these needs. Therefore, e-commerce will be a major driving force and an important enabler for shaping the future of mass customization.

Rapid communication over the Internet will revolutionize not only trade but also all the business functions. A paradigm of electronic design and commerce (eDC) can be envisioned as shown in Figure 14. Further expanded to the entire enterprise, it is often referred to as electronic enterprise (eEnterprise). Three pillars support eDC or eEnterprise: the integrated product life cycle, mass customization, and the supply chain.

The integrated product life cycle incorporates elements that are essential to companies, including marketing/sales, design, manufacturing, assembly, and logistics. Using the Internet, some of these activities may be handed over to the supply chain. There may also be other companies similar to the regular supply chain that supplies services. These constitute business-to-service functions.

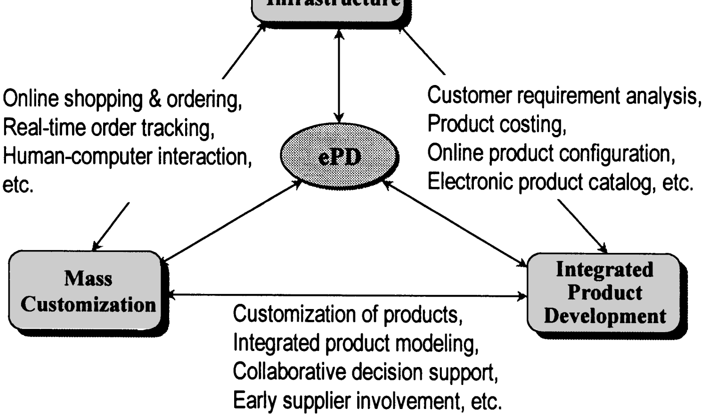

Figure 14 A Systems Model of eDC/eEnterprise.

With the communication and interactivity brought by the Internet, the physical locations of companies may no longer be important. The common business model with a core company that engages in design, manufacturing, and logistics will become less common. Manufacturing, as well as design and logistics, may, for example, be conducted by outside service companies. As a result, in view of the supply chain and service companies, the core of business-to-business e-commerce is flourishing.

Figure 14 also illustrates a systems approach to manufacturing. It is a dynamic system with feedback. For each new product or customized design, one must go around the loop. The purpose is to obtain information from marketing and other sources to estimate customer needs. The product life cycle is therefore illustrated by one full circle around the system.

The company can sell products to distributors and/or directly to customers through business-to-customer e-commerce. In some cases, products may be designed by the customer himself or herself. This is related to mass customization. Customer needs are then captured directly through the customers' preferences—the customers understand what they want and can submit their preferred design electronically. A well-known example is Dell Computers, where customers can select the elements that constitute a computer according to their own preferences.

Usually information about customer needs may be delivered by sales and marketing. Typically, they rely on analyses of customer feedback and predictions for the future. These remain important sources of information for new product development. From this kind of information, the company may redesign existing products or decide to develop a new one. The design effort has to take place concurrently, with many experts involved representing various areas of expertise and parties that collaborate through the system. The supply chain companies may also participate if necessary.

For manufacturing the product, parts and/or other services may be bought from the supply chain and delivered just-in-time to manufacturing facilities. These constitute typical business-to-business e-commerce.

Some important technical issues associated with eDC include human–computer interaction and usability (Helander and Khalid 2001), the customer decision-making process over the Internet (So et al. 1999), product line planning and electronic catalog, and Web-based collaborative design modeling and design support.

6. SUMMARY

Mass customization aims at better serving customers with products and services that are closer to their needs and building products upon economy of scale leading to mass production efficiency. To this end, an orchestrated effort in the entire product life cycle, from design to recycle, is necessary. The challenge lies in how to leverage product families and how to achieve synergy among different functional capabilities in the value chain. This may lead to significant impact on the organizational structure of company in terms of new methods, education, division of labor in marketing, sales, design, and manufacturing. The technological roadmap of mass customization can also lead to redefinition of job, methodology, and investment strategies as witnessed in current practice. For instance, the sales department will be able to position itself to sell its capabilities instead of a group of point products.

As a new frontier of business competition and production paradigm, mass customization has emerged as a critical issue. Mass customization can best be realized by grounding up, instead of by directly synthesizing, existing thrusts of advanced manufacturing technologies, such as JIT, flexible, lean and agile manufacturing, and many others. Obviously, much needs to be done. This chapter provides materials for stimulating an open discussion on further exploration of mass customization techniques.

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