CONCURRENT ENGINEERING: Research and Applications

Generic Bill-of-Materials-and-Operations for High-Variety Production Management

Jianxin Jiao,[1,*] Mitchell M. Tseng,[2] Qinhai Ma[2] and Yi Zou[2]

[1]*School of Mechanical and Production Engineering, Nanyang Technological University,*
Nanyang Avenue, Singapore, 639798

[2]*Department of Industrial Engineering and Engineering Management,*
The Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong

Received 8 May 2000; accepted in revised form 6 September 2000

Abstract: High-variety production like mass customization is facing the challenge of effective variety management, which needs to deal with numerous variants of both product and process in order to accommodate diverse customer requirements. To utilize commonality underlying product diversity and process variation, it has been widely accepted as a practice to develop product families, in which a set of similar variants share common product and process structures and variety differentiates within these common structures. Based on such variety implication, this paper proposes a data structure, called generic Bill-of-Materials-and-Operations (BOMO), by unifying Bills-of-Materials (BOM) and routing data into a single set in order to synchronize multiple perspectives on variety such as customer ordering, product engineering, and operations planning. A generic structure is accordingly developed for characterizing variety effectively. The merits of the generic BOMO for integrated product and production data management are detailed in terms of order processing, engineering change control, production job planning, cost accounting, as well as integrated material and capacity planning. An implementation of the proposed generic BOMO methodology in customized souvenir clock manufacturing is also reported.

Key Words: Bill-of-Materials, variety management, mass customization, assembly-to-order, product data management, production information management, concurrent engineering, product family.

1. Introduction

As an emerging paradigm of manufacturing, mass customization (Pine, 1993) has received enormous attention and popularity in industry and academia alike. With an increasingly global economy, industries are moving towards customer-oriented production (Wortmann et al., 1997). Mass customization production aims at satisfying individual customer needs while keeping near mass production efficiency (Tseng and Jiao, 1996). With mass customization production, individual customers are allowed to specify product characteristics, i.e., product differentiation, which results in a wide variety of manufactured products. Child et al. (1991) pointed out that variety initially improves sales as the offering becomes more attractive, but that as variety increases the law of diminishing returns means the benefits do not keep pace. 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 both flexibility and agility are provided by advanced manufacturing machinery such as CNC-machines. These facilities accommodate technical variety (Jiao, 1998) originating from diverse needs of customers. However, at the front end, from customer needs to product engineering and to production planning, managing variety is still very *ad hoc*. For example, production control information systems, such as MRPII (Manufacturing Resource Planning) or ERP (Enterprise Resource Planning), are falling behind even though they are important ingredients of production management (Erens et al., 1994). The difficulties arise from the need to specify all possible variants of a product, and from that current production management systems are often designed to support production of only a limited number of product variants (Van Veen, 1992).

The challenges of data management associated with high-variety production can be observed as follows.

(1) *Data explosion:* The traditional approach to variant handling is to treat every variant as a separate product by specifying a unique Bill-of-Materials (BOM) for each vari-

---

*Author to whom correspondence should be addressed. E-mail: mjiao@ntu.edu.sg

1531-2003/00/04 0297–25 $10.00/0 DOI: 10.1106/95P6-GB09-YHG6-H5QG

ant. This works with a low number of variants but not when customers are granted a high degree of freedom for 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 deal with a large number of variants, it is necessary to understand the implication of variety and to characterize variety effectively.

(2) *Data redundancy:* The development of product families has been recognized as an effective means of supporting variety (McKay et al., 1996). A number of models containing partial and complete descriptions of the structure of a product are created and utilized throughout the product development and innovation process. Research in the area of product structure is mainly presented in terms of product modeling, which typically deals with detailed data related to an individual product (Krause et al., 1993; Jiao and Tseng, 1999a). In industry, product structures and associated coding systems are usually specific to particular product families, which results in large amounts of redundant product data. In order to minimize data redundancy, the representation of product families is different from traditional product modeling in that product data have to be related to both families of products and specific product variants in a single context. In other words, instead of a collection of individual product variants, the organization of product data needs to explicate the relationships between variants, which should reflect the common structure of each product family as well as the derivation of variants from a certain family structure.

(3) *Data comprehensiveness:* Increasing variety has far-reaching influence on many organizational functions such as sales and marketing, product engineering, and manufacturing. The commercial department is primarily engaged in processing customer-specific orders, which involves final-product configuration and quotations of cost and delivery time. Due to variety, engineering change control becomes a serious problem for the design department. Tasks of production management such as costing, production planning, and shop floor control also become more difficult due to increasing process variations and operations changeovers. One study has suggested that, in most engineering companies, poor change control could cost up to 10% of turnover (Harvey-Robson, 1990). Since a company-wide product data model across various product families rarely exists in practice (Bei and MacCallum, 1995), it is necessary to synchronize diverse types of product data from multiple business perspectives. For example, for sales and marketing, it must be possible to represent product specifications in terms of functional parameters and constraints, and in the meantime be able to describe end products, subassemblies, and components, along with their relationships, for the engineering purpose.

(4) *Data separation:* Traditionally, PDM (Product Data Management) technologies enhance the manageability of large amounts of product data such as engineering documents and drawings, part lists and BOMs. While PDM is engineering-oriented and focuses on the product structure in the form of a BOM, production information management is operation-oriented and emphasizes the process structure in the form of routings (Tatsiopoulos, 1996). These two groups of data, together with work centers as capacity units, form the basic elements of the manufacturing process (Bertand et al., 1990). It has been pointed out that MRPII has achieved only limited success in its industrial implementation and the shortfall is due to fundamental weakness of its planning logic (Mather, 1986; Berger, 1987), that is, the lack of integration between MRP (Material Requirements Planning) and capacity requirements planning. The separate implementation of planning and control functions of MRPII seems in accordance with the separation of BOM components and routing operations (Yeh, 1997). For better coordination in an extended enterprise, e.g., ERP, an integrated product and production data management is necessary (Prasad, 1996), in which the major concern is the unification of traditional BOMs and operations routings (Tatsiopoulos, 1996).

Towards this end, this paper discusses integrated product and production data management for mass customization production characterized by a high variety. A data structure, called Bill-of-Materials-and-Operations (BOMO), is proposed for the purpose of unifying BOMs and routings in order to facilitate better production planning and control, order processing, and engineering change control. To deal with variety effectively, the concept of a generic BOMO is put forward. A generic variety structure is also developed to characterize variety effectively. The merits of the generic BOMO for integrated product and production data management are detailed in terms of order processing, engineering change control, MRP, production job planning, costing, and capacity planning.

In the next section, the background leading to this research is summarized. Section 3 introduces the concept of BOMO as well as the rationale of a generic BOMO with respect to variety management. The application of the generic BOMO to integrated product and production management for mass customization production is presented in Section 4. Discussion and future work are outlined in Section 5, and the paper is concluded in Section 6.

2. Background Review

In its simplest form, the BOM defines "items or raw materials that go into the product" (Garwood, 1988). Cox et al. (1992) emphasized the linkages between components and parents by defining the BOM as a "list of all the subassemblies, intermediate parts, and raw materials that go into a parent assembly showing the quantity of each required to make an assembly." Essentially being a structured part list, the BOM is usually employed in production management to explode the Master Production Schedule (MPS) into both gross and net component requirements. In summary, a BOM should involve three aspects as described below.

(1) *Items:* The way in which a product is built from purchased parts and/or semi-finished products (which, in turn, consist of other semi-finished products and/or purchased parts) is called the product structure of that product. As the component of a product structure, an item might be a purchased part (raw material), an intermediate part or a subassembly, or a final product (Hegge, 1992).

(2) *Goes-into relationships:* A goes-into relationship is a relationship between a particular parent and a particular component (Van Veen, 1992). Usually, the number of units of the component required for one unit of the parent is stored together with the goes-into relationship. This number is called the *quantity per* of the relationship. A BOM may contain several goes-into relationships, all with the same parent product. All goes-into relationships, together with items, form a hierarchy representing the product structure.

(3) *Employment:* In practical applications, the BOM takes various forms and is used in a number of ways. From different perspectives of business functions, the content and construction of BOM will be different. For example, an engineering BOM is structured in the way the product is designed and consists of functional "assemblies" of subsystems, whilst a manufacturing BOM is structured in the way the product is built and consists of physical subassemblies. While the engineering BOM is used by designers to represent the structure of a designed product, the manufacturing BOM is used in a MRPII system for MRP explosion. Other perspectives may include product definition, engineering change control, manufacturing instructions, order entry facility, costing, and pricing (Mather, 1987).

2.1 BOM Construction

Although many names and definitional distinctions appear in the literature, common types of BOMs constructed for the planning purpose include modular BOM (MBOM), percentage BOM (PBOM), Super BOM (SBOM), variant BOM (VBOM), and generic BOM (GBOM).

While the traditional BOM links components to end items (the top level of the BOM), a MBOM links components to product options, which is below the end product level (Van Veen and Wortmann, 1992). A MBOM is constructed in the way the product is ordered and consists of product feature modules (called planning modules). A planning module is identified as a set of parts that is commonly required within a product family for realizing certain options of final products. It is often assumed that a planning module corresponds to an option, thus options (or planning modules) can be applied to identify a final product uniquely and in the meantime to constitute the BOM of that final product. Therefore, individual product variants can be specified from different combinations of planning modules by composing single-level BOMs consisting of planning modules.

In a situation of high-variety production, the traditional method of BOM construction may require a large number of different bills because each model, option, or product variation necessitates a unique BOM. Modularization reduces the number of bills by segregating common parts and disentangling product feature combinations (Stonebraker, 1996). However, the problem of an enormous number of BOMs can only be partly solved by modularizing BOMs due to the formidable hindrances underlying the MBOM method (Van Veen and Wortmann, 1992). First, it is assumed that there is one-to-one correspondence between a planning module and an option. In this case, the BOM of a planning module defines the full material content required to realize a particular option (Mather, 1987). Second, options of different features are assumed to be uncoupled from each other. In other words, an option can be selected for a feature independently of selecting options for other features. Third, the overlap of material requirements for options is ignored. If options of the same feature have lower-level components in common, the products common to these options would be overplanned for each of these options, resulting in more safety stock than is actually required. Fourth, in a MBOM, the assembly hierarchy of the product structure is blurred. It is difficult to support the creation of an assembly BOM after a unique product specification in terms of options has been drafted.

A PBOM captures the proportional composition of either parts or modules to support the translation of the forecast volume of product family as a whole into the volumes of components. It can be used with either traditional or modular BOMs to facilitate cost accounting by calculating the average cost for each model. Since the forecast and planning of an aggregate are generally more accurate than those of components, the PBOM may enhance product forecast and scheduling efficiency (Mather, 1987).

A SBOM augments MBOM and PBOM with add/delete bills as attachments (Kneppelt, 1984). Minor product variations are handled by a simple add/delete attachment representing only the change, thus avoiding the creation of a complete new BOM. Using the SBOM approach, marketing could furnish a model forecast and the estimate on the percentage use of options and attachments. It also provides an opportunity to coordinate the option planning better since some overplanning may happen on the options to compensate for percentage forecast errors.

The VBOM concept emphasizes various goes-into relationships in a BOM structure, which are called BOM relationship variants (Van Veen, 1992). A set of BOM relationship variants of an item is partitioned into explicitly defined subsets called clusters so that each specific BOM consists of precisely one element out of each cluster. The entire set of BOM relationship variants that have an item as the parent is called the VBOM of this item. The VBOM concept enables generative BOM processing in the way that a specific multi-level BOM can be constructed by selecting none or one BOM relationship variant from each cluster in the multi-level VBOM. For each cluster in the VBOM, a set of rules (called conditions) can be defined to express the dependencies between BOM relationship variants of that cluster according to different parameter values.

While the VBOM excels in generative BOM processing especially in those situations where product variety arises at the top-levels of the product structure, the limitations have also been observed by Van Veen and Wortmann (1992). The VBOM concept allows parameters and parameter values to be defined for product family items only because product specification data (i.e., parameters, parameter values and conditions) are exclusively related to product variants. As a result, variety of a lower-level item can not be described in terms of its own characteristic parameters and parameter values. In addition, the fact that lower-level product variants can only be explicitly defined for end items results in considerable data redundancy in parameters, parameter values and conditions.

To overcome the limitations of the VBOM in variant handling, the GBOM concept has been developed (Hegge and Wortmann, 1991; Hegge, 1992; Van Veen, 1992; Van Veen and Wortmann, 1992). The GBOM allows the specification of product variants by means of describing an item and a set description at any level in a multilevel BOM instead of limited only to top-level items. A GBOM represents the general product structure of a set of similar product variants (i.e., a product family). The representation of such a GBOM consists of two entity types, i.e., the *generic item* representing sets of similar items and the *generic BOM link* recording the link between a generic parent and a generic component. A specific variant results from the choice of the variants of their generic item and the specification of particular goes-into relationships derived from the instantiation of the generic BOM links according to certain conversion rules. The rationale lies in the reduction of variant differences to the variants of the generic items at the lowest level of the GBOM.

The GBOM concept provides a means of describing a large number of variants within a product family using a limited amount of data, while leaving the product structure unimpaired. It can be used for describing both final products and components. Current practice of the GBOM concept mostly focuses on variety management in the context of product structures, which is engineering-oriented. Since the variety dilemma involves both product engineering and production management, the consequence of variety's propagation to production deserves the further exploration of the GBOM concept in terms of dealing with various process variations and operations changeovers.

In summary, all these types of BOMs enhance productivity and integrate operational goals with broader organization objectives. However, migration from traditional to modular BOMs and to other supplemental methods has reduced the applicability of the BOM to operational functions because the representation of the production process is less accurate (Stonebraker, 1996). Therefore, it is imperative for BOM research to extend the traditional engineering-oriented BOM construction to take into account production structures and operations management.

2.2 BOM Employment

Many organizational functions within a manufacturing firm make use of BOM systems. The traditional function of BOM is the definition of a product from the design point of view only. Under MRP, however, the function of BOM is extended to reflect product content, state of completion, timing, and/or process stage. Master production scheduling further extends the employment of BOM. A BOM must provide the structure for decision support at the top planning level. It forms the basis for developing forecasts, assembly schedules, and customer order control within the functional area of master scheduling (Mather, 1987). A well-known problem is that each of these functions has different requirements regarding the definition of one or more product-types and the associated attributes. Therefore, many firms face problems with respect to the coherence and synchronization of various kinds of BOM employment.

A matrix BOM is suggested for MBOM planning in order to improve the construction of product catalogs (Kneppelt, 1984). To support the unique description of a product variant for the purpose of order entry and to support the selection of a product for a particular customer, a catalog number is derived from a sales catalog system and it becomes the unique part number for this customer order. Such a unique part number is the basis for inventory, transaction processing, and shipping. Marketing may also configure a product based on the sales potential and the result is a product on the shelf. Naturally, forecasting and master scheduling must be based on the unique part numbers at the product level, since this is the entry point of customer demand.

Chang et al. (1997) discussed the planning of manufacturing BOM which involves compressing the multi-level engineering BOM into a three-level manufacturing BOM. The compression assigns components of the engineering BOM into several assembly groups by considering the assembly sequence and manufacturing constraints. The major concern of this method is the formulation of assembly groups incorporating assembly lead-time, assembly liaison and precedence, and concurrent assembly.

Aiming at integrated production data modeling, Hastings and Yeh (1992) proposed a concept of bill of manufacture (BOMfr). The BOMfr combines routings with traditional BOMs to provide material requirements data for each operation scheduled, resulting in a time-phased material requirement plan derived from a feasible schedule. Blackburn (1985) demonstrated how combining routings and BOMs in one document could support just-in-time manufacturing in a traditional MRP-implemented production environment such as job-shops. Tatsiopoulos (1996) discussed the consequences of unifying BOMs and routings on the basic functions of production planning and control. The MRP planning logic based on the unification of BOMs and routings avoids the intricacies of the OPT (Optimized Production Technology) system and is more readily accepted by manufacturing personnel.

3. Generic Bill-of-Materials-and-Operations

3.1 Illustrative Example

The running example in this paper is the customization and production of souvenir clocks. One souvenir clock package includes a desk clock and a customer-decorated paper box. The focus is on product information management and production planning and control. The problem scenario assumes that families of desk clocks have been designed in a modular manner to maximize product assortment, thus allowing customers to have more choices. The product assortment, structure, and components have been planned with great care to facilitate product customization and assembly.

Figure 1 shows the structure of a desk clock. Figure 2 gives an example of product family structure developed to offer functional variety and a high degree of configuring individual products. A simple product family structure with a small number of variant components results in low complexity and ease of assembly. Besides fixed variant components such as the base part, the front plate, and the setting of hands, both the dial and the label sticker can be individualized during production by printing the customer's name or picture on them. Different family structures can be developed for different product families in order to accommodate certain product assortments.

The manufacturing process flow for souvenir clock production is described in Figure 3. The process involves five assembly operations (A1, A2, A3, A4, and A5), two machining operations (M1 and M2), and one printing operation (M3). As illustrated in Figure 3, some parallel operations are possible. Each operation is associated with a particular work center concerning material requirements, machines or assembly workstations, processing time, fixtures/setups, and operation instructions for operators. There is a separate kitting activity prior to each operation (K1, K2, K3, K4, K5, K6, and K7), in which all materials required for this operation are prepared according to MRP.

The production of souvenir clocks is based on a manual Flexible Assembly System (FAS) implemented at HKUST. Figure 4 shows the layout of this system. The system consists of an Automatic Storage and Retrieval System (AR/RS), a magnetic path-guided Automatic Guided Vehicle (AGV), and a Computer-controlled Transport System (CTS) with flexible routing.

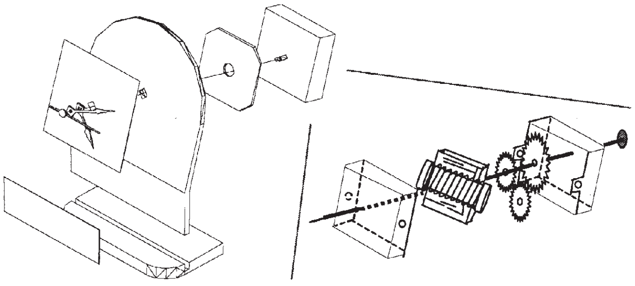


Figure 1. The structure of a desk clock.

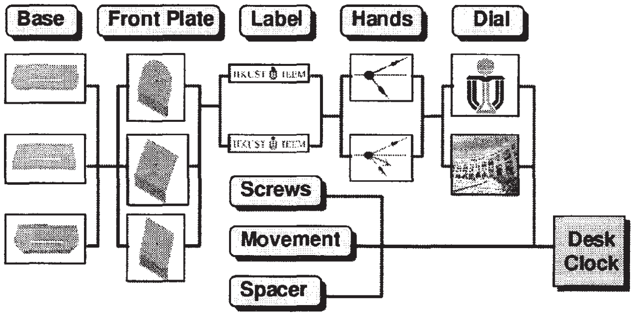


Figure 2. A family structure of various desk clocks.

Five manual assembly workstations are connected to the CTS in accordance with the five assembly operations. Material handling between workstations is carried out by shuttles running on the CTS. At a kitting workstation, the necessary parts for subsequent assembly operations are prepared and put together into a kit. The kit is then transferred using a shuttle to the assembly workstation where the assembly is to be performed. Due to the fact that the AGV is the major bottleneck in the system because of its relatively slow speed, commonly-used parts, especially bulk materials such as hands and screws, are transferred in large quantities from the AS/RS to the CTS at one time and are stored in grab containers at kitting workstations. While the fabrication of frame parts (bases and front plates) is carried out at CNC machines (M1 and M2), the dial of a personalized clock, label stickers for the clock and the packaging box are printed out directly at the workbench. The final product is transferred to a packaging workstation where final testing and checking is conducted and the clock is put into a paper box, ready for delivery. In addition, all operations conducted at these workstations by workers are supported by instructions shown on computer screens in the form of text, image and animation. Although several kinds of clocks (clock families) can be produced, it is not necessary to retool the FAS for each of them. It is possible to produce mixed orders without retooling delays.

3.2 Bill-of-Materials-and-Operations (BOMO)

A logic representation of product data and production information plays an important role in production planning and control for performing functions such as material requirements planning (MRP), capacity requirements planning, operations scheduling, and shop-floor control (Orlicky, 1994).

Product data represented by a BOM can be used for describing an end product to state raw materials and intermediate parts or subassemblies required for making the product. Figure 5 shows the BOM structure of souvenir clocks. Table 1 gives the corresponding BOM data records in a traditional BOM file structure.

Production information is concerned with how a product is

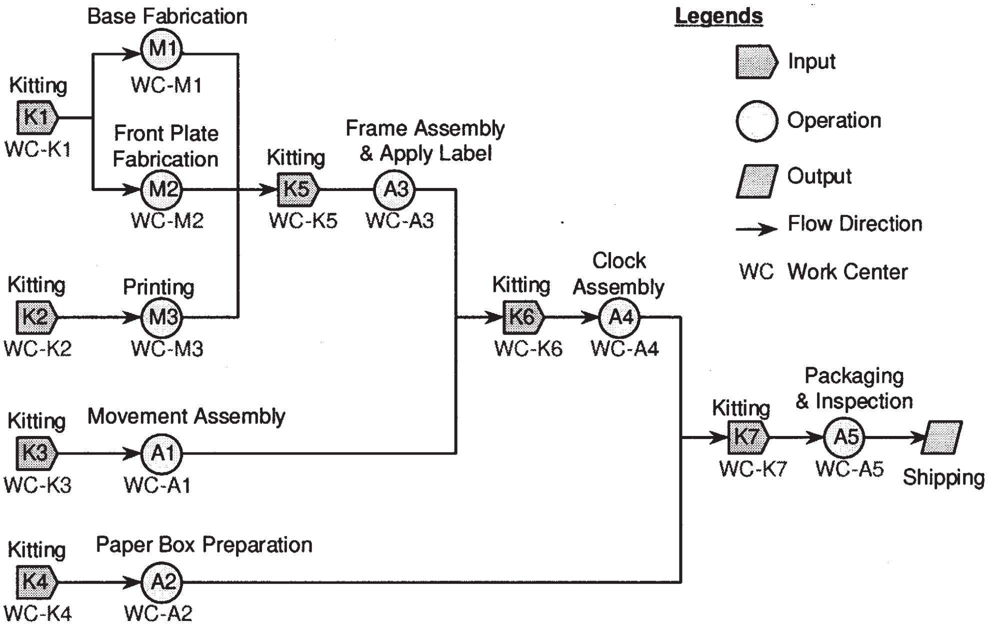


Figure 3. A process flow diagram describing the production process of souvenir clocks.

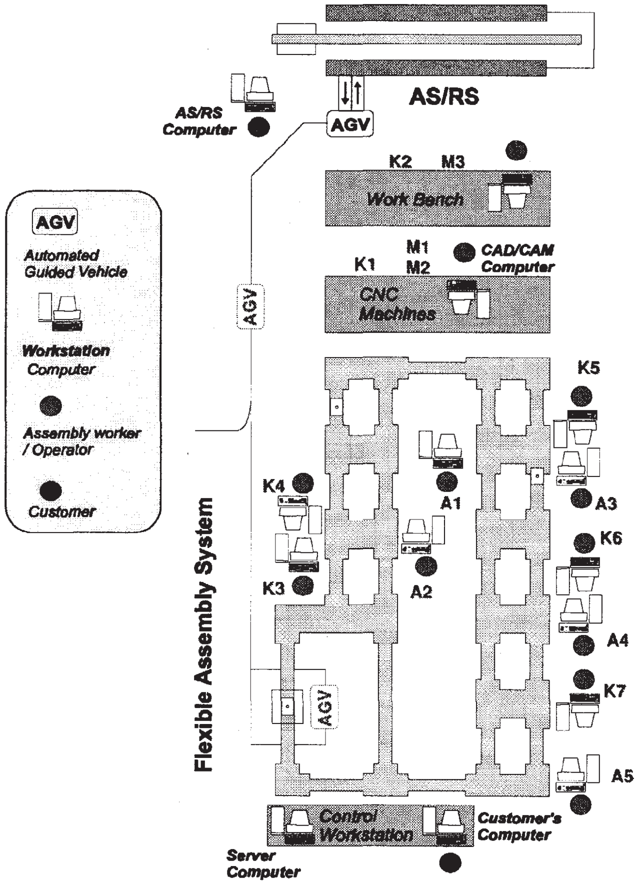


Figure 4. The layout of a manufacturing system for souvenir clock production.

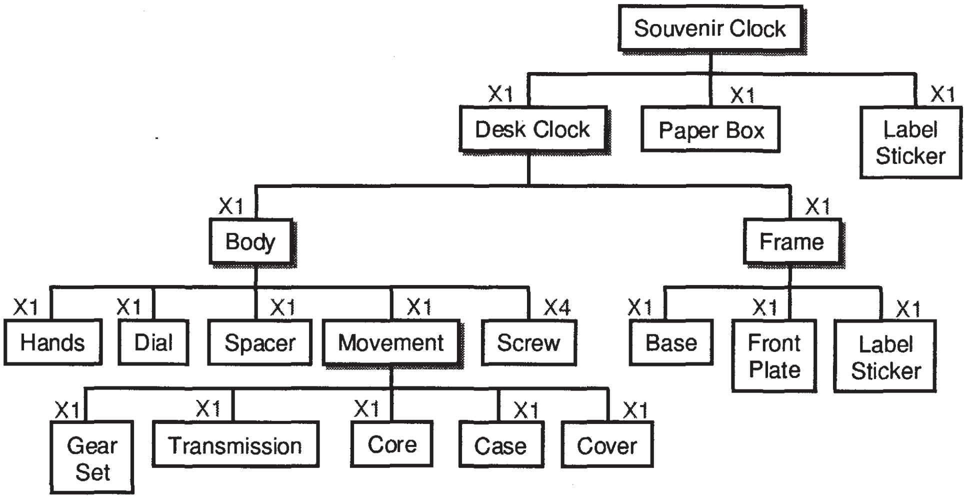


Figure 5. The BOM structure of souvenir clocks.

produced, i.e., the specification of operations sequences to be performed at corresponding work centers along with related resources such as machines, labor, tools, fixtures and setups. Similar to describing a product structure using a BOM, a Bill-of-Operations (BOO) can be constructed to represent the production structure of a given product. A BOO manifests itself through the process flow diagram that is widely used in industry to describe the manufacturing process, for example the one shown in Figure 3. The corresponding operations data (BOO) of each manufactured end product and intermediate part/subassembly in Figure 5 is given in Table 2.

Traditionally, BOMs and BOOs have been treated as two separate data files or subsystems by most computer-based production systems (Mather, 1986). The separation of production planning and control functions into a BOM and a BOO results in the BOM being primarily responsible for MRP and inventory management, and the BOO being responsible for capacity requirements planning and production control (Berger, 1987). In a job-shop environment, jobs (work orders) are created and scheduled to make every line item of a customer order. A line item corresponds to an end product manufactured by the shop. A job is a statement of making a product, which requires both BOM and BOO data. An effective control of a production job at the shop-floor level cannot be fulfilled without the integration of planning and control functions. This necessitates that the material content of a BOM be linked to the relevant operations of a BOO to reflect the material flow through the production process (Yeh, 1995). A number of authors have demonstrated the merits of integrating the BOM and the BOO in production planning and control (Tatsiopoulos, 1996; Hastings and Yeh, 1992; Yeh, 1997).

To integrate product structure data and operations information, a formal data model, referred to as Bill-of-Materials-and-Operations (BOMO), can be developed by combining the BOM structure with the BOO structure into a single one. Focusing on the production process, a BOMO specifies the sequence of production operations required for making an intermediate part/subassembly or a final product as well as the materials and resources required at each operation. In this way, the unification of BOMs and BOOs can be achieved in a BOMO structure, as schematically illustrated in Figure 6. Corresponding to Tables 1 and 2, the BOMO data of the souvenir clock example is given in Table 3.

For a given product, the relationships between its BOM and BOO are embodied in the material requirements of production operations. Therefore, a product's BOM and BOO data can be merged into a single data set by specifying each component material in the BOM as required by the relevant operation of the BOO for making its parent product (Mather, 1987).

As conceptually described in Figure 6, the material re-

Table 1. BOM data for end product souvenir clock.

Hierarchy Level	Parent Item	Component Item	Quantity per
1	Souvenir Clock	Desk Clock	1
1	Souvenir Clock	Paper Box	1
1	Souvenir Clock	Label Sticker	1
.2	Desk Clock	Body	1
.2	Desk Clock	Frame	1
..3	Body	Hands	1
..3	Body	Dial	1
..3	Body	Spacer	1
..3	Body	Movement	1
..3	Body	Screw	4
..3	Frame	Base	1
..3	Frame	Front Plate	1
..3	Frame	Label Sticker	1
…4	Movement	Gear Set	1
…4	Movement	Transmission	1
…4	Movement	Core	1
…4	Movement	Case	1
…4	Movement	Cover	1

Table 2. **BOO data for souvenir clock production.**

Sequence Number*	Operation	Work Center	Runtime (min/item)	Fixture/ Setup
90	Packaging & Inspection (A5)	WC-A5	1.5	
80	Kitting (K7)	WC-K7	1.0	
70	Clock Assembly (A4)	WC-A4	14.0	A4-F
60	Kitting (K6)	WC-K6	1.0	
70	Paper Box Preparation (A2)	WC-A2	2.0	
60	Kitting (K4)	WC-K4	4.5	
50	Frame Assembly (A3)	WC-A3	11.5	A3-F
40	Kitting (K5)	WC-K5	1.0	
50	Movement Assembly (A1)	WC-A1	11.0	A1-F
40	Kitting (K3)	WC-K3	4.5	
30	Base Fabrication (M1)	WC-M1	12.5	M1-F
30	Front Plat Fabrication (M2)	WC-M2	14.5	M2-FS
20	Kitting (K1)	WC-K1	9.0	
30	Printing (M3)	WC-M3	3.0	
20	Kitting (K2)	WC-K2	2.0	

*Same sequence numbers indicate parallel operations.

quirement link between BOM and BOO data can be established by introducing a part kitting process to each operation. Kitting is widely used in industry to convert as much of the internal setup as possible into the external setup in order to reduce setup costs, which constitutes a large proportion of the overall cost of assembly. In the FAS shown in Figure 4, the concept of kitting has been extended to include not only component parts but also tools and fixtures. In addition, kitting flow strategies are closely integrated with the material handling function. The kitting system interfaces with the material distribution system (AGV) as well as the warehouse (AR/RS) and the production system (work centers).

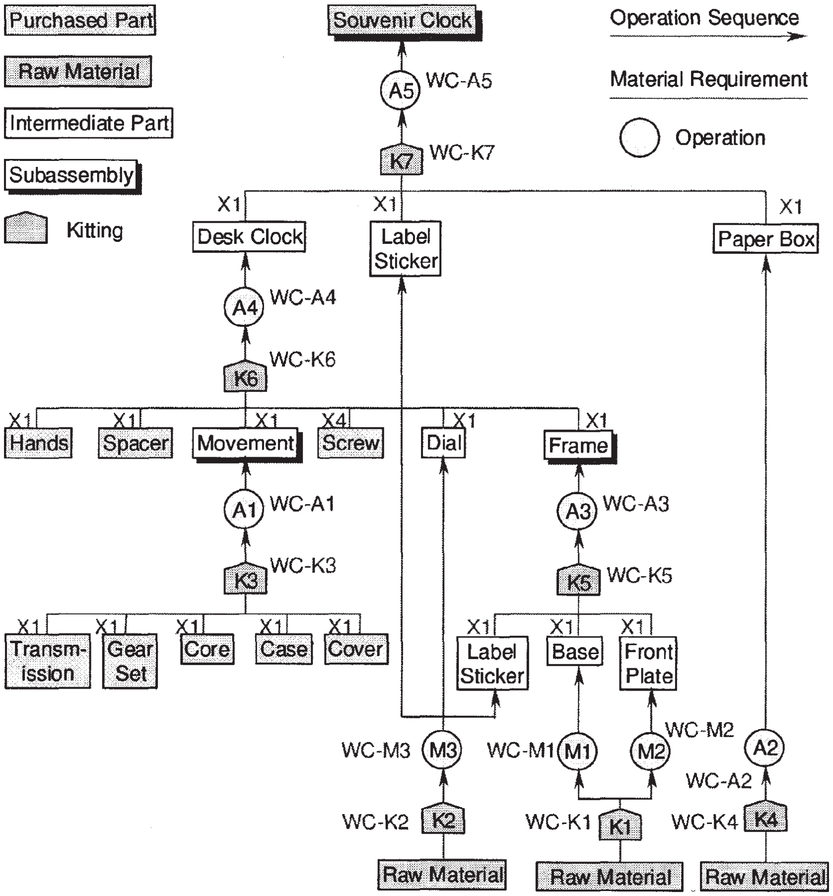


Figure 6. The BOMO structure of souvenir clocks.

Table 3. BOMO data for souvenir clocks.

Sequence Number*	Operation	Work Center	Runtime (min/item)	Fixture/ Setup	Material (Component Item)	Product (Parent Item)	Quantity per
90	Packaging & Inspection (A5)	WC-A5	1.5		Desk Clock	Souvenir Clock	1
80	Kitting (K7)	WC-K7	1.0		Label Sticker		1
					Paper Box		1
70	Clock Assembly (A4)	WC-A4	14.0	A4-F	Hands	Desk Clock	1
60	Kitting (K6)	WC-K6	1.0		Spacer		1
					Movement		1
					Screw		4
70	Paper Box Preparation (A2)	WC-A2	2.0		Raw Material (Board)	Paper Box	1
60	Kitting (K4)	WC-K4	4.5				
50	Frame Assembly (A3)	WC-A3	11.5	A3-F	Base	Frame	1
40	Kitting (K5)	WC-K5	1.0		Front Plate		1
					Label Sticker		1
50	Movement Assembly (A1)	WC-A1	11.0	A1-F	Gear Set	Movement	1
40	Kitting (K3)	WC-K3	4.5		Transmission		1
					Core		1
					Case		1
					Cover		1
30	Base Fabrication (M1)	WC-M1	12.5	M1-F	Raw Material	Base	N/A
30	Front Plate Fabrication (M2)	WC-M2	14.5	M2-FS		Front Plate	
20	Kitting (K1)	WC-K1	9.0				
20	Printing (M3)	WC-M3	3.0		Raw Material	Label Sticker	N/A
10	Kitting (K2)	WC-K2	2.0			Dial	

*Same sequence numbers indicate parallel operations.

In a general sense, each operation can be regarded as consisting of a kitting process prior to the actual production process. A kitting process can be either implicit or explicit. An explicit kitting refers to a productive process for which a separate work center is assigned. An implicit one, however, is nonproductive in the sense that it is combined to an operation workstation as a part of that operation, thus being a dummy production process. In an assembly line, usually only one explicit kitting process is assigned as a single workstation while all assembly operations are associated with implicit kitting within their own workstations.

While a BOM associates each component material directly with its parent product, a BOMO associates a component material with the relevant operation in the BOO for producing its parent component. For each manufactured end or intermediate product, a single-level BOMO structure can be derived by specifying the sequence of operations required for producing that product as well as materials and resources (work centers) required for each operation. The multi-level BOMO can be composed by linking the single-level BOMOs of lower-level intermediate parts through the operations that require them.

3.3 A Generic Structure for Characterizing Variety

To understand variety and its impact on product differentiation, Jiao and Tseng (1999a) introduced a generic structure established for representing variety. As schematically illustrated in Figure 7, there are three aspects underlying the generic variety structure, i.e.,

1. *Product structure:* All product variants of a family share a common structure. It can be described as a hierarchy comprising 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 together with 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 (characteristic variables), $\boldsymbol{A}$, associated with each I_i. Among them, some variables are relevant to variety and thus are defined as variety parameters, $\{P_j\} \subset \boldsymbol{A}$. Like attribute variables, parameters can be inherited by child node(s) from a parent node. Different instances of a particular P_j, i.e., $\{V_k\}$, 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, which means $I2$ has several variants in terms of values of $P2$, i.e., $V2 \sim \{V2\_1, V2\_2\}$.

3. *Configuration constraints:* Two types of constraints can be identified. Within a particular view of product families such as the functional, behavioral or physical view, restrictions on the combination of parameter values, $\{V_k\}$, are categorized as Type I constraints. For example, *V11-1_1* and *V31-3_2* are incompatible (i.e., exclusive OR), that is, only one of them can be selected for a product variant. 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 (Jiao, 1998), this research focuses on the production aspect, which is mostly concerned with the structural view. Therefore, in the context of managing variety in production, the major concern is Type I constraints.

Table 4 illustrates the generic variety structure described above using the souvenir clock example. As far as variant handling is concerned, the rationale for the generic variety structure lies in the recognition of the origin and subsequent propagation of variety. Three levels of variation have been indicated, i.e., 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, the following 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 (namely a family). An 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 frame (I_1^*), a blue frame (I_2^*) and a transparent one (I_3^*) are three individual variants, whilst a generic item, $\boldsymbol{I}$, represents such a set of variants (a family of frames), that is, $\boldsymbol{I} \sim \{I_1^*, I_2^*, I_3^*\}$. However, these variants are similar in that they share a common structure (Figure 5) in configuring a desk clock.
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 of parameter values). Such an identification is called indirect identification (Hegge, 1994). In the above example, a variety parameter, color, and its value list, {red, blue, transparent}, can be used for an indirect identification of a particular variant, i.e., $I_1^* \sim \{\boldsymbol{I} \mid \text{color} = \text{"red"}\}$ and $I_3^* \sim \{\boldsymbol{I} \mid \text{color} = \text{"transparent"}\}$. On the other hand, the identification of product family (generic product) "frame" is $\boldsymbol{I}$.

3.4 Generic BOMO for Variety Management

Based on the generic variety structure, a generic BOMO can be constructed to deal with variants resulting from both product changes and process variations. The premise of constructing a generic BOMO lies in the implications of variety underlying product families, that is, a set of variants (a family

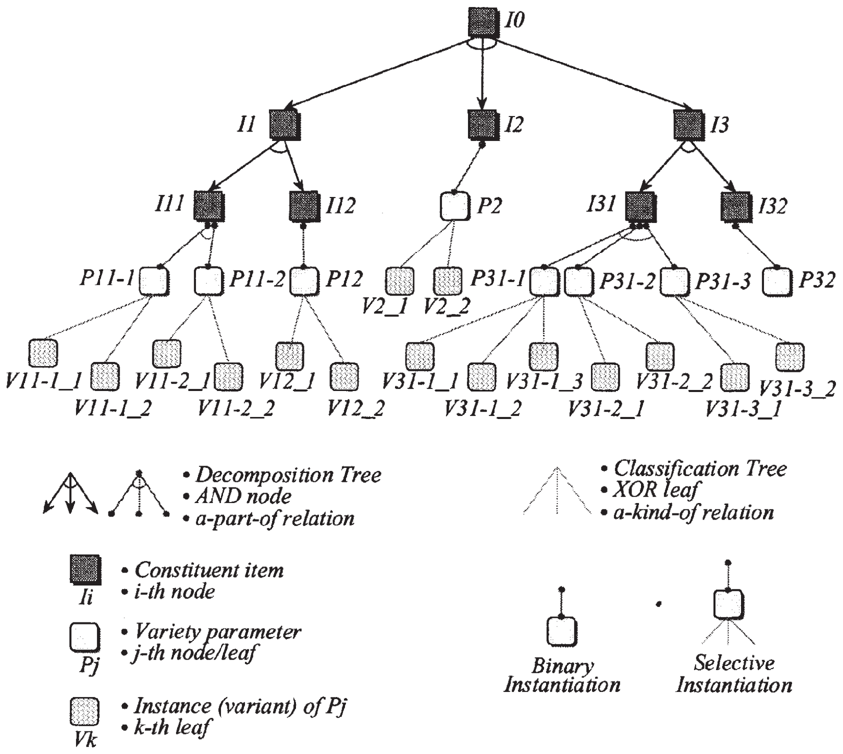


Figure 7. A generic structure for characterizing variety.

Table 4. The generic variety structure for souvenir clocks.

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

Table 5. An illustration of the generic product in a generic BOMO.

Generic Product $\{I_i\}$	Variety Parameter $\{P_{ij}\}$	Parameter Value Set $\{P^*_{ijk}\}$
Frame (I_1)	Nil.	Nil.
Base (I_2)	Shape (P_{21})	Round (P^*_{211})
		Rectangular (P^*_{212})
		Hexagonal (P^*_{213})
	Material (P_{22})	Acrylic (P^*_{221})
		Aluminum (P^*_{222})
	Color (P_{23})	Red (P^*_{231})
		Transparent (P^*_{232})
		Blue (P^*_{233})
Front Plate (I_3)	Shape (P_{31})	Round (P^*_{311})
		Rectangular (P^*_{312})
		Rhombus (P^*_{313})
	Material (P_{32})	Acrylic (P^*_{321})
		Aluminum (P^*_{322})
	Color (P_{33})	Red (P^*_{331})
		Transparent (P^*_{332})
		Blue (P^*_{333})
Label Sticker (I_4)	Pattern (P_{41})	HKUST (P^*_{411})
		Signature (P^*_{412})
		IEEM (P^*_{413})

of similar items) share a common (product/process) structure within which variety differentiates.

There are four elements constituting a generic BOMO as described below.

(1) *Generic product:* A generic product represents a family of product variants, where a product may manifest itself through a final product, an intermediate part, a subassembly, or a component part. A list of variety parameters, $\{P_{ij}\}$, is assigned to each generic product, $\boldsymbol{I}_i$, and each parameter has a number of parameter values, $\{P^*_{ijk}\}$, going with it. A particular variant, I^*_i, of a generic product, $\boldsymbol{I}_i$, is obtained by choosing a permitted set of values, $\{P^*_{ijk}\}$, for the variety parameter, $\{P_{ij}\}$, of $\boldsymbol{I}_i$, that is, $I^*_i \sim \{P^*_{ijk}\}$. Table 5 illustrates such a concept of generic product in the generic BOMO. For example, the generic product "base" can be described by parameters, "shape," "material" and "color" with permitted values {Round, Rectangular, Hexagonal}, {Acrylic, Aluminum} and {Red, Transparent, Blue}, respectively. A "base" variant may be described as {shape(round), material(acrylic), color(red)}, that is, $I^*_2 \sim \{P^*_{211}, P^*_{221}, P^*_{231}\}$.

(2) *Generic goes-into relationship:* A generic goes-into relationship represents the relationship between a parent generic product and a component generic product in accordance with the decomposition hierarchy of a product family structure. Accordingly, a specific goes-into relationship (a variant of the generic goes-into relationship) represents the particular BOM relationship between a specific parent product and a specific component product. Different from a goes-into relationship variant, a generic goes-into relationship involves the coordination of multiple variants (parameter values) while exploding a generic BOM. Therefore, explosion rules are introduced to generic goes-into relationships. These rules define deterministic relationships between parameter values in the product specifications of parent product variants and component product variants. The rules should guarantee that for each valid specification of the parent product, precisely only one valid specification of the component product is generated through the explosion process. Essentially, explosion rules reflect all Type I constraints identified in the generic variety structure. The general form of an explosion rule is as follows.

$$\{P_{ij} \mid P^*_{ijk}\} \text{ IF } \{P_{xy} \mid P^*_{xyz}\} \text{ AND } \ldots$$

$$\text{AND } \{P_{mn} \mid P^*_{mnp}\} \text{ OR } \ldots$$

$$\text{OR } \{P_{qr} \mid P^*_{qrs}\} \qquad (1)$$

$$\{P_{ij} \mid P^*_{ijk}\} \text{ IIF } \{P_{xy} \mid P^*_{xyz}\} \qquad (2)$$

where, IIF means if and only if.

Table 6 shows an example of the generic goes-into relationship in a generic BOMO. The "material" and "color" constraints between a "base" variant and a "front plate" variant (see Table 4) are described in the corresponding explosion rules. These rules define that only the same material, either {Acrylic} or {Aluminum}, can be used in specifying "base" and "front plate" variants. Also, the rules indicate that the color of a "base" variant or that of a "front plate" variant can be selected freely from {Red} and {Blue}, whilst {Transparent} must be used at the same time for both "base" and "front plate" variants. Essentially, the explosion rules represent a choice tree of instantiating variety parameters by their feasible values, that is, to reflect Type I constraints. Corresponding to Table 6, Figure 8 shows the decision table, described using the generic variety structure, for the specification of "frame" variants from a generic "frame" product.

(3) *Generic operation:* Table 7 illustrates the generic operation concept. A generic operation, $\boldsymbol{O}$, represents a set of

Table 6. An illustration of the generic goes-into-relationship in a generic BOMO.

Hierarchy Level	Parent Product	Component Product	Explosion Rule	Quantity per
..3	Frame ($\boldsymbol{I}_1$)	Base ($\boldsymbol{I}_2$)	Material (P_{22}) constraint: $\{P_{22} \mid P^*_{221}\}$ IIF $\{P_{32} \mid P^*_{321}\}$ $\{P_{22} \mid P^*_{222}\}$ IIF $\{P_{32} \mid P^*_{322}\}$ Color (P_{23}) constraint: $\{P_{23} \mid P^*_{231}\}$ IF $\{P_{33} \mid P^*_{331}\}$ OR $\{P_{33} \mid P^*_{332}\}$ $\{P_{23} \mid P^*_{232}\}$ IF $\{P_{33} \mid P^*_{331}\}$ OR $\{P_{33} \mid P^*_{332}\}$ $\{P_{23} \mid P^*_{233}\}$ IIF $\{P_{33} \mid P^*_{333}\}$	1
..3	Frame ($\boldsymbol{I}_1$)	Front Plate ($\boldsymbol{I}_3$)	Material (P_{32}) constraint: $\{P_{32} \mid P^*_{321}\}$ IIF $\{P_{22} \mid P^*_{221}\}$ $\{P_{32} \mid P^*_{322}\}$ IIF $\{P_{22} \mid P^*_{222}\}$ Color (P_{33}) constraint: $\{P_{33} \mid P^*_{331}\}$ IF $\{P_{23} \mid P^*_{231}\}$ OR $\{P_{23} \mid P^*_{232}\}$ $\{P_{33} \mid P^*_{332}\}$ IF $\{P_{23} \mid P^*_{231}\}$ OR $\{P_{23} \mid P^*_{232}\}$ $\{P_{33} \mid P^*_{333}\}$ IIF $\{P_{23} \mid P^*_{233}\}$	1
..3	Frame ($\boldsymbol{I}_1$)	Label Sticker ($\boldsymbol{I}_4$)	Nil.	1

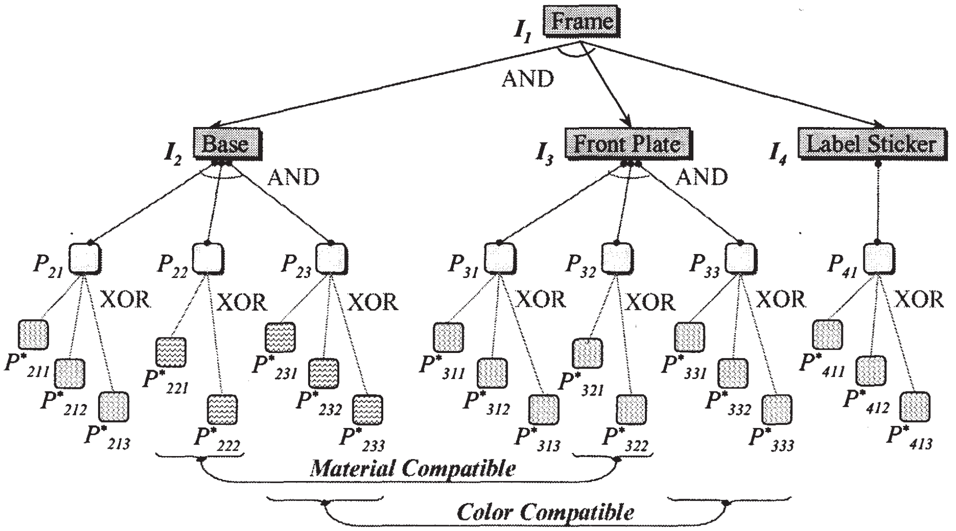


Figure 8. A choice tree for the generic goes-into-relationship in Table 6.

variants of an operation, $\{O^*\}$. These operation variants manifest themselves in different process-related information (e.g., process plans) of each operation. Such information can be regarded as the attributes of an operation. Usually, the operation attributes involve the following aspects:

- parts to be processed
- work centers for producing particular parts such as machine (cells) or assembly workstations
- the runtimes of certain parts processed by particular work centers
- the tool, fixture and/or setup requirements necessary for making particular parts on particular work centers

Therefore, a generic operation, $\boldsymbol{O}$, can be described in terms of its attributes in a tuple, i.e., $\boldsymbol{O} \sim \{(Part, WC, RT, FS)\}$, where *Part, WC, RT* and *FS* denote the generic part, generic work center, generic runtime and generic tool/fixture/setup requirements associated with the generic operation, respectively. Accordingly, a specific operation variant, O^*, can be described by its attribute values, i.e., $O^* \sim (Part^*, WC^*, RT^*, FS^*)$, where $Part^*$, WC^*, RT^* and FS^* denote the specific part(s), work center(s), runtime(s) and tool/fixture/setup requirements, respectively.

There are a number of ways to categorize various operation variants. As pointed out earlier, the link between product structures (BOMs) and production operations (BOOs) is characterized by the material requirement of each operation (see Figure 6). Therefore, it is reasonable to differentiate operation variants using variety parameters defined for the (generic) parts involved in a (generic) operation. As shown in Table 7, a generic operation is linked to the generic parts to be processed on it through sharing the same set of variety parameters as well as their value sets. In such a way, the identification of an operation variant (a specific process plan for a particular part variant) conforms to the way a product variant is identified, for example, $M\,1^*_1 \sim (Base(hexagonal, acrylic, transparent), WC\text{-}M\,1^*_2, 12.5 + 3.0, M1\text{-}F^*_1)$, where *M1* represents the generic operation, "Base Fabrication" (see Figure 6 and Table 2).

(4) *Generic planning:* Generic planning refers to the representation of all process variations in operations planning for producing a generic product (a family of product variants). Typically, the major concern in the generic planning is to indicate the corresponding changeovers in routings to accommodate variations of product variants. Variations of an operation are determined by the differences in product variants to be processed by this operation. For example, different variants of a "base" product in terms of "color" have no impact on the operation changeover. In other words, one operation variant may produce multiple product variants regardless of their differences in "color." However the use of different "materials" (P^*_{221} and P^*_{222}) may result in quite different processes ($M1^*$) in terms of different instances of work centers, runtime, tools and fixtures. Such a nonlinear correspondence relationship between product variants and operation variants necessitates the definition of planning rules as shown in Table 8.

The general form of planning rules follows the same format of Equations (1) and (2) defined for the explosion rules. Since MRP establishes the link of BOM and BOO data, variety parameters and their value sets are uniformly applicable to characterizing both product and operation variants through defining explosion and planning rules.

In summary, a generic BOMO integrates product and production data together through the link of MRP between BOMs and BOOs. To manage variety effectively, variety parameters and their value sets are used to handle the coherence between the variants of products and those of operations. In a generic variety structure, all variety parameters are controlled at the lowest level of the decomposition hierarchy so as to ease the coordination of different variants and to reduce

Table 7. An illustration of the generic operation in a generic BOMO.

Generic Operation **{*O*}**	**Generic Parts** **{I_i}**	**Variety Parameter** $\{P_{ij}\}$	**Parameter Value Set** $\{P^*_{ijk}\} \sim \{(C^*_{ijk}, WC^*_{ijk}, RT^*_{ijk}, FS^*_{ijk})\}$			
			Part $\{Part^*_{ijk}\}$	**Work Center** $\{WC^*_{ik}\}$	**Runtime** $\{RT^*_{ik}\}$	**Fixture/Setup** $\{FS^*_{ik}\}$
Base Fabrication (M1)	Base ($\boldsymbol{I}_2$)	Base.Shape (P_{21})	Round (P^*_{211}) Rectangular (P^*_{212}) Hexagonal (P^*_{213})	WC-M1^*_1 WC-M1^*_2	RT^*_{21} (= 12.5 + 4.5) RT^*_{22} (= 12.5 + 3.0) RT^*_{23} (= 12.5 + 1.0)	M1-F^*_1 M1-F^*_2 M1-F^*_3
		Base.Material (P_{22})	Acrylic (P^*_{211}) Aluminum (P^*_{222})	Notes: Machines/Machine cells/ Workstations for making particular parts	RT^*_{24} (= 12.5 – 2.0)	Notes: Tools/Fixtures/ Setups for making particular parts on particular work centers
		Base.Color (P_{23})	Red (P^*_{213}) Transparent (P^*_{232}) Blue (P^*_{233})		Notes: (minute/item)	
Front Plate Fabrication (M2)	Front Plate ($\boldsymbol{I}_3$)	FrontPlate.Shape (P_{31})	Round (P^*_{311}) Rectangular (P^*_{312}) Rhombus (P^*_{313})	WC-M2^*_1 WC-M2^*_2	RT^*_{31} (= 14.5 + 5.0) RT^*_{32} (= 14.5 + 2.5) RT^*_{33} (= 14.5 + 0.0)	M2-F^*_1 M2-F^*_2 M2-F^*_3
		FrontPlate.Material (P_{32})	Acrylic (P^*_{321}) Aluminum (P^*_{322})	Notes: Machines/Machine cells/ Workstations for making particular parts	RT^*_{34} (= 14.5 – 3.5)	Notes: Tools/Fixtures/ Setups for making particular parts on particular work centers
		FrontPlate.Color (P_{33})	Red (P^*_{331}) Transparent (P^*_{332}) Blue (P^*_{333})		Notes: (minute/item)	

Table 8. An illustration of the generic planning in a generic BOMO.

Sequence #	Operation	Part	Planning Rule (*WC*, *RT*, *FS*)
30	Base Fabrication (M1)	Base (I_2)	$\{WC \mid \text{WC-M1}_1^*\}$ IF $\{P_{22} \mid P_{221}^*\}$ $\{WC \mid \text{WC-M1}_2^*\}$ IF $\{P_{22} \mid P_{222}^*\}$ $\{RT \mid RT_{21}^*\}$ IF $\{P_{22} \mid P_{221}^*\}$ AND $\{P_{21} \mid P_{213}^*\}$ $\{RT \mid RT_{22}^*\}$ IF $\{P_{22} \mid P_{221}^*\}$ AND $\{P_{21} \mid P_{211}^*\}$ OR $\{P_{21} \mid P_{212}^*\}$ $\{RT \mid RT_{23}^*\}$ IF $\{P_{22} \mid P_{222}^*\}$ AND $\{P_{21} \mid P_{213}^*\}$ $\{RT \mid RT_{24}^*\}$ IF $\{P_{22} \mid P_{222}^*\}$ AND $\{P_{21} \mid P_{211}^*\}$ OR $\{P_{21} \mid P_{212}^*\}$ $\{FS \mid \text{M1-F}_1^*\}$ IF $\{\mathrm{P}_{21} \mid P_{211}^*\}$ $\{FS \mid \text{M1-F}_2^*\}$ IF $\{\mathrm{P}_{21} \mid P_{212}^*\}$ $\{FS \mid \text{M1-F}_3^*\}$ IF $\{\mathrm{P}_{21} \mid P_{213}^*\}$
30	Front Plate Fabrication (M2)	Front Plate (I_3)	$\{WC \mid \text{WC-M2}_1^*\}$ IF $\{P_{32} \mid P_{321}^*\}$ $\{WC \mid \text{WC-M2}_2^*\}$ IF $\{P_{32} \mid P_{322}^*\}$ $\{RT \mid RT_{31}^*\}$ IF $\{P_{32} \mid P_{321}^*\}$ AND $\{P_{31} \mid P_{313}^*\}$ $\{RT \mid RT_{32}^*\}$ IF $\{P_{32} \mid P_{321}^*\}$ AND $\{P_{31} \mid P_{311}^*\}$ OR $\{P_{31} \mid P_{312}^*\}$ $\{RT \mid RT_{33}^*\}$ IF $\{P_{32} \mid P_{322}^*\}$ AND $\{P_{31} \mid P_{313}^*\}$ $\{RT \mid RT_{34}^*\}$ IF $\{P_{32} \mid P_{322}^*\}$ AND $\{P_{31} \mid P_{311}^*\}$ OR $\{P_{31} \mid P_{312}^*\}$ $\{FS \mid \text{M2-FS}_1^*\}$ IF $\{P_{31} \mid P_{311}^*\}$ $\{FS \mid \text{M2-FS}_2^*\}$ IF $\{P_{31} \mid P_{312}^*\}$ $\{FS \mid \text{M2-FS}_3^*\}$ IF $\{P_{31} \mid P_{313}^*\}$

data redundancy in variety representation. Hence, explosion rules and planning rules can be defined in terms of constraints among parameter values. Nevertheless, all variants of a generic product are assumed to conform to the same product structure and the same process flow (sequences). This means that there exist a common product structure and a common process structure within a product family, whilst variety is embodied in different variants (instances) of these common structures.

3.5 Object-Oriented Modeling of Generic BOMO

The structure of a generic BOMO can be regarded as the abstraction hierarchy of an object-oriented data model. From this point of view, its representation can be mapped onto the abstraction and the inheritance architectures of an object-oriented data model. Inherently, the indirect identification of variants from a generic product through variety parameters and their values conforms to the class-member relationship of the object-oriented concept. However, one major difficulty in representing the semantics of a data model is that no universally accepted theory of object-oriented data modeling exists (Booch, 1990). This research employs a conceptual data model that integrates elements of semantic relationships with object oriented concepts for the purpose of representing a generic BOMO.

(1) *Conceptual data model:* Three classes of objects belong to subclasses of the root class, CLASS (Figure 9). A PRODUCT object represents the superclass of subclasses that defines a specific constituent item. Its major subclasses might be COMPONENT, SUBASSEMBLY, and END-PRODUCT object classes. A PROCESS object represents the superclass of subclasses that defines the operations routings of constituent items. A CONSTRAINT object represents the superclass of subclasses that defines the configuration constraints on PRODUCT objects (goes-into relationships) and on PROCESS objects (routings). EXPLOSION-RULE and PLANNING-RULE are subclasses of CONSTRAINT. These classes can be referenced to one another.

An object is a collection of information related to performing specific tasks that involve a lot of data and certain relationships and support a variety of methods related to handling instance objects. The semantics of relationships between objects is shown in Figure 9. PRODUCT objects are aggregated or decomposed through "part_of" or "has_a" relationships. They also have "referencing" relationships with PROCESS objects ("referenced_by" for reverse). A "kind_of" relationship manifests the generalization of subclasses into a superclass.

(2) *Construction of classes:* The definitions of PRODUCT and PROCESS classes are based on the frame representation. Details of the formal representation language can be found in Jiao and Tseng (1999a). These classes are initialized for any object when the object is created. To synchronize product and production data, PRODUCT objects communicate with PROCESS objects through "referencing" relationships. Inversely, PROCESS objects may interact with PRODUCT objects through "referenced_by" relationships. Aggregation of particular PROCESS objects comprises a particular opera-

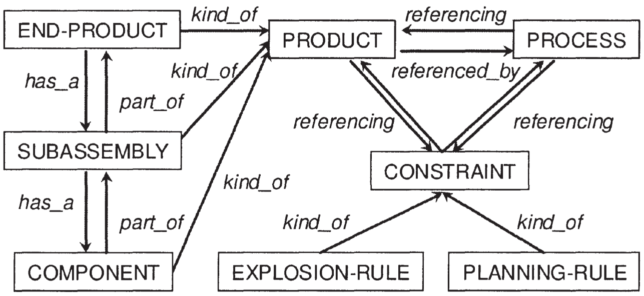


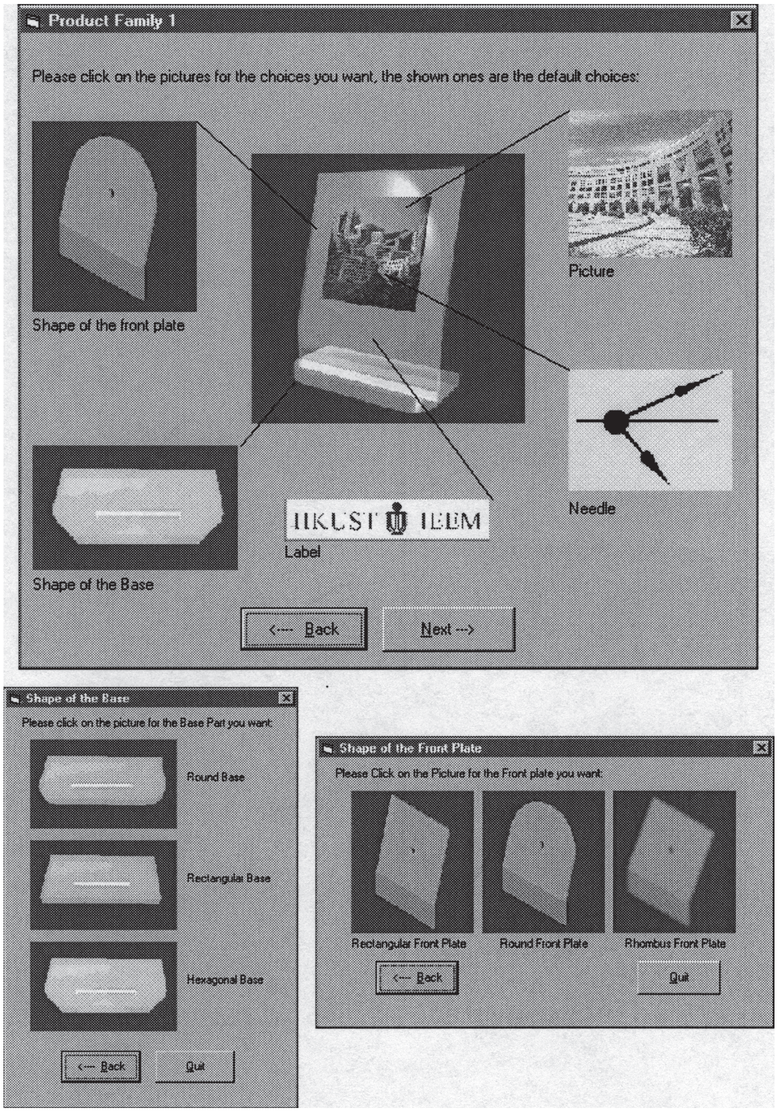
Figure 9. The class and relationship hierarchies for generic BOMO modeling.

tions plan for a certain PRODUCT object at either product or subassembly or component level.

(3) *Semantic relationships:* If one object has an attribute that is a reference to another object, this means a relationship exists between the objects. The “referencing” relationship means that an attribute is a character string that is the unique identification of the referenced object, or it is an address pointer to the object. To make relationships meaningful, certain operations are needed, which are performed by sending messages and executing methods, along with defining the semantics of the relationships. Objects communicate with one another by sending messages and receiving responses via one-to-one correspondence.

3.6 A Prototype of Generic BOMO Processing System

A prototype system for BOMO processing based on the generic BOMO methodology described above has been implemented using KAPPA-PC® 2.4 (Kappa-PC, 1998) as a development tool. Two functions are necessary for a BOMO processing system, namely the *product specification* function in which a product variant is merely identified by means of parameter values and the *BOMO generation* function in which a BOM and the corresponding BOO is generated for a product variant identified by means of parameter values. In particular, if the product specification process is a part of the order entry function for customer orders, additional support may be required to compose specifications that are both valid and suitable. Therefore, sometimes a third process is distinguished, namely the *customer specification support* process. While the product specification process merely aims at achieving a valid specification, the customer specification support function advises the user (in general a salesman or customer) in the selection of parameter values that produce the specification of the product vari-



Please click on the pictures for the choices you want, the shown ones are the default choices:

Please click on the picture for the Base Part you want:

Please Click on the Picture for the Front plate you want:

Figure 10. An example of customer specification support.

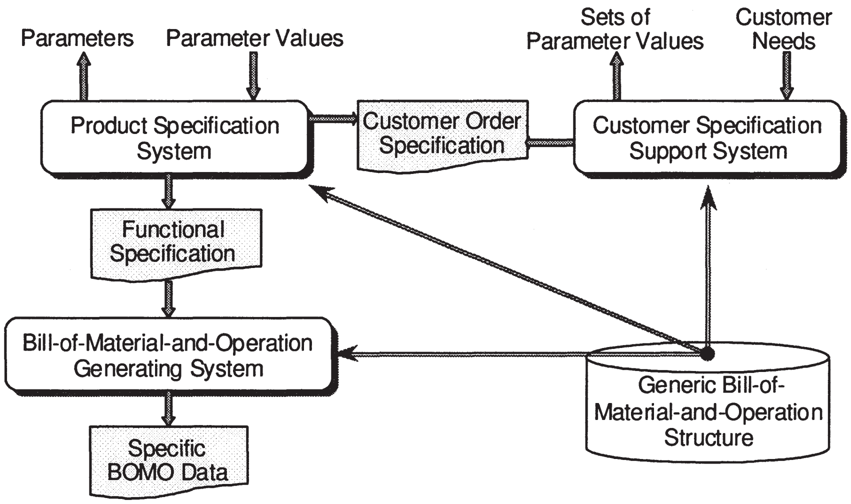


Figure 11. An architecture for BOMO processing and order entry systems.

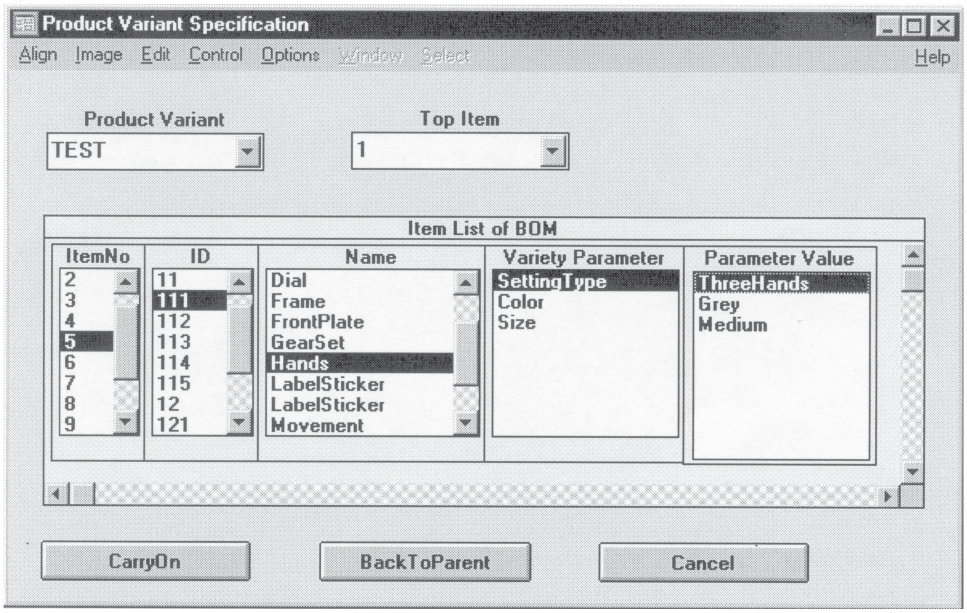
ant most suitable for the user. Figure 10 shows an example of customer specification support for souvenir clocks. Figure 11 highlights the resulting system architecture consisting of three subsystems necessary for BOMO processing, namely the customer specification support system (for sales), the product specification system (for marketing), and the BOMO generating system (for product and production engineers). While Table 4 constitutes the most important element of customer specification support, Table 12 shows an example of the functional specification, and an example of the specific BOMO data is given in Tables 9 and 10. Figure 12 shows an example of deriving specifications for an individual product variant based on the generic BOMO. Figure 13 illustrates how configuration constraints are depicted as IF-THEN rules in Kappa-PC, where fuzzy rules are possible using the priority settings of the rule description.

Table 9. A specific BOM variant derived from the generic BOMO for an individual customer order.

Hierarchy Level	Generic Item	Parameters	Parameter Value	Quantity per
1	Desk Clock (I_1)			1
1	Paper Box (I_2)	Type	Delux	1
1	Label Sticker (I_3)	Pattern	HKUST	1
.2	Body (I_{11})			1
.2	Frame (I_{12})			1
..3	Hands (I_{111})	Setting Type Color Size	Three-Hand Grey Medium	1
..3	Dial (I_{112})	Pattern Size	Photo Medium	1
..3	Spacer (I_{113})			1
..3	Movement (I_{114})			1
..3	Screw (I_{115})			4
..3	Base (I_{121})	Shape Material Color	Round Acrylic Transparent	1
..3	Front Plate (I_{122})	Shape Material Color	Rectangular Acrylic Transparent	1
..3	Label Sticker (I_{123})	Pattern	HKUST	1
...4	Gear Set (I_{1141})			1
...4	Transmission (I_{1142})	Alarm	Yes	1
...4	Core (I_{1143})	Alarm	Yes	1
...4	Case (I_{1144})			1
...4	Cover (I_{1145})			1

Table 10. Specific production job data for making the product variant of Table 9 (volume = 5).

Job #	Sequence #	Operation	Work Center	Runtime (min/item × Lot Size)	Fixture/ Setup	Product (Lot Size)	Component/Material (Quantity)	Component Job #
100	90	Packaging & Inspection	WC-A5	1.5 × 5		Souvenir Clock (1 × 5)	Desk Clock (1 × 5)	99
	80	Kitting	WC-K7	1.0 × 5			Label Sticker (1 × 5)	94
							Paper Box (1 × 5)	98
99	70	Clock Assembly	WC-A4	14.0 × 5	A4-F	Desk Clock (1 × 5)	Hands (1 × 5)	N/A
	60	Kitting	WC-K6	1.0 × 5			Spacer (1 × 5)	N/A
							Movement (1 × 5)	96
							Screw (4 × 5)	N/A
98	70	Paper Box Preparation	WC-A2	2.0 × 5		Paper Box (1 × 5)	Raw Material (1 set ×5)	N/A
	60	Kitting	WC-K4	4.5 × 5				
97	50	Frame Assembly	WC-A3	11.5 × 5	A3-F	Frame (1 × 5)	Base (1 × 5)	95
	40	Kitting	WC-K5	1.0 × 5			Front Plate (1 × 5)	95
							Label Sticker (1 × 5)	94
96	50	Movement Assembly	WC-A1	11.0 × 5	A1-F	Movement (1 × 5)	Gear Set (1 × 5)	N/A
	40	Kitting	WC-K3	4.5 × 5			Transmission (1 × 5)	N/A
							Core (1 × 5)	N/A
							Case (1 × 5)	N/A
							Cover (1 × 5)	N/A
95	30	Base Fabrication	WC-$M1_1^*$	(12.5 + 3.0) × 5	M1-F_1^*	Base (1 × 5)	Raw Material (1 set ×5)	N/A
	30	Front Plate Fabrication	WC-$M2_2^*$	(14.5 + 2.5) × 5	M2-FS_2^*	Front Plate (1 × 5)		
	20	Kitting	WC-K1	9.0 × 5				
94	20	Printing	WC-M3	3.0 × 2 × 5		Label Sticker (2 × 5)	Raw Material (1 set ×5)	N/A
	10	Kitting	WC-K2	2.0 × 2 × 5		Dial (1 × 5)		



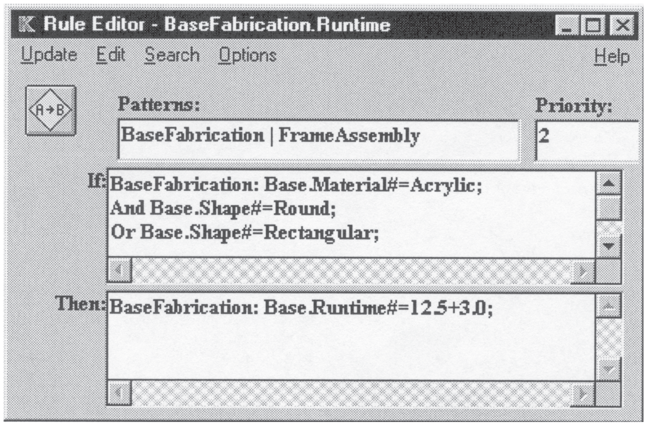
Product Variant: TEST

Top Item: 1

Item List of BOM

ItemNo	ID	Name	Variety Parameter	Parameter Value
2	11	Dial	SettingType	ThreeHands
3	111	Frame	Color	Grey
4	112	FrontPlate	Size	Medium
5	113	GearSet		
6	114	Hands		
7	115	LabelSticker		
8	12	LabelSticker		
9	121	Movement		

Figure 12. Generating a product variant specification.



Patterns: BaseFabrication | FrameAssembly

Priority: 2

If: BaseFabrication: Base.Material#=Acrylic;
And Base.Shape#=Round;
Or Base.Shape#=Rectangular;

Then: BaseFabrication: Base.Runtime#=12.5+3.0;

Figure 13. An example of planning rules in Kappa-PC.

4. Integrated Product and Production Data Management for High-Variety Production

A generic BOMO implies two types of relationships, namely the product-material relationship and the operation-material relationship. While the product-material relationship reveals the material requirements for making each product variant, the operation-material relationship indicates the logical material flow through its production process (Yeh, 1995). From these relationships, the material-resource relationship can be derived to list all products and materials to be processed or consumed at a work center, together with the associated labor, runtime, tools, fixtures and setups. Therefore, the coherence of material requirement planning and production planning can be achieved, in the meantime accommodating a wide range of production variations and product variety.

(1) *Engineering change control:* An engineering change usually refers to a change to the form, fit or function of a product or part (Maull et al., 1992). For the purpose of production management, changes must be made to the BOM file and be managed as a part of the engineering change control process. Failure to manage this process invariably results in the *ad hoc* introduction of both new designs and design changes, together with the inevitable deterioration in production performance. In a situation of mass customization production characterized by small quantities, short life cycles and high diversity, engineering changes become more serious due to large amounts of trivial BOM changes for various customized product variants. Based on pre-defined product structures embedded in a generic BOMO, such engineering changes can be effectively managed through defining a specific BOM for each individual customer order according to different values of variety parameters. Table 9 gives an example of defining a specific product variant for an individual customer.

In addition, a generic BOMO object can be regarded as a kind of pseudo product in the sense that it describes both structure and process information of a physical product. In order to maintain a complete object description, it is important that the lowest-level components are attached to their parent product. Then every change in the parent product, due to construction changes, re-specification, change of completion date, order cancellation, etc., will also affect the subcomponents. For example, a postponement of the finishing date for the top-level product automatically leads to a postponement of the required date for all sub-components. Ideally, any update of the generic BOMO object should result in an identical modification of the requirement for the physical product. If components have already been produced or purchased, the consequences of a modification should also be informed.

Furthermore, product "individuality" may come both from customer specifications (called planned individuality), and from exceptions during production, an *ad hoc* form of individuality (Olsen and Saetre, 1997; Olsen et al., 1997). It is important to be able to express both forms as parts of the generic BOMO object. The planned individuality is needed in order to define which components go into a certain product variant and to control the manufacturing process. The *ad hoc* individuality ensures that the generic BOMO object acts as a description of the actual physical product. Such "as built" structures become important when the manufacturer, through service programs, also takes responsibility for the product after it has been taken over by the customer. The "as built" structure may then be updated by service date, in order to maintain the identity relationship between the generic BOMO object and the physical product.

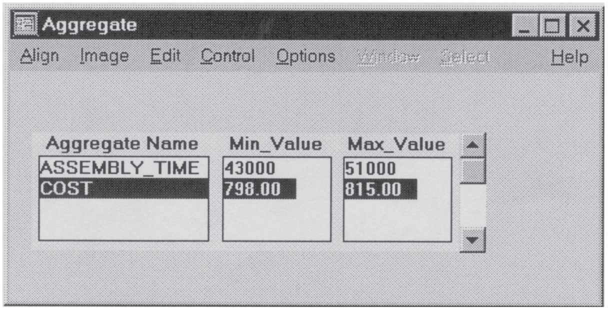
(2) *Production job planning:* The generic BOMO provides a planning standard according to which all reporting formats of the conventional BOM and the routing for specific needs can be generated. Production jobs represent the current work to be manufactured in order to meet specific demands. The creation of production jobs and the planning of their variations to produce particular products can be derived from the relevant elements of a generic BOMO with the addition of appropriate job attributes such as operation routing, material requirements data, batch size, due data and job sequences. Table 10 shows the production job data planned for making the product variant in Table 9. In the table, component jobs created for making intermediate products impose job sequence constraints on the job for making their higher level product. A job processing a higher level product cannot start until its component jobs are completely or partially finished. Production job data forms a basis for detailed operations scheduling and shop-floor control. Their maintenance is independent of the generic BOMO data, thus facilitating the routine planning of producing standard or variant products. Jobs can be easily created to allow various batch sizes and job attributes. This also allows for flexible manipulation of a wide range of production variations such as re-routing, alternatives of routing and material, tools, fixtures and setups.

(3) *Integrated material and capacity planning:* The main function of MRP is to determine the materials required for production by quantity and time. From the generic BOMO, a finite capacity-constrained production schedule can be created. The quantity of materials required by each operation is calculated from the job data derived from the generic BOMO and the date required is the planned feasible start time of that operation in the production schedule (Yeh, 1997). Aggregated gross material requirement reports for a time period and for a certain volume of end products (lot size) can be generated for each type of material required in the production schedule (see Table 10).

Based on the generic BOMO, an integrated material and capacity planning is feasible. This can be accomplished by relating the time-phased, operation-associated requirements of each item to particular work centers and by allowing production engineers to include product and production properties such as the total component cost, assembly time, the labor and overhead costs, etc. in a list of aggregates. As shown in Table 10, the aggregate runtime for a work center can be

Table 11. Costing data for the product variant in Tables 9 and 10 (volume = 5).

Manufacturing Costs							Material Costs			
Operation	**Work Center**	**Labor Rate ($/hour)**	**Overhead Rate ($/hour)**	**Runtime (min/item × Lot Size)**	**Labor Cost ($)**	**Overhead Cost ($)**	**Raw Material**	**Unit Cost ($/item)**	**Quantity Quan. per (Volume)**	**Material Cost ($)**
Packaging & Inspection	WC-A5	7.0	7.5	1.5 × 5	0.875	0.938				
Kitting	WC-K7	5.0	8.0	1.0 × 5	0.417	0.667				
Clock Assembly	WC-A4	11.0	8.5	14.0 × 5	12.83	9.917	Hands (I_{111})	0.1	1 × 5	0.5
Kitting	WC-K6	5.0	8.0	1.0 × 5	0.417	0.667	Spacer (I_{113})	0.05	1 × 5	0.25
							Screw (I_{115})	0.03	4 × 5	0.6
Paper Box Preparation	WC-A2	5.0	5.0	2.0 × 5	0.833	0.833	Paper Box (I_{2})	0.3	1 × 5	1.5
Kitting	WC-K4	5.0	8.0	4.5 × 5	1.875	3.0				
Frame Assembly	WC-A3	8.5	12.0	11.5 × 5	8.146	11.5				
Kitting	WC-K5	5.0	8.0	1.0 × 5	0.417	0.667				
Movement Assembly	WC-A1	11.0	11.0	11.0 × 5	10.083	10.083	Gear Set (I_{1141})	0.24	1 × 5	1.2
Kitting	WC-K3	5.0	8.0	4.5 × 5	1.875	3.0	Transmission (I_{114})	0.2	1 × 5	1.0
							Core (I_{1143})	0.98	1 × 5	4.9
							Case (I_{1144})	0.18	1 × 5	0.9
							Cover (I_{1145})	0.18	1 × 5	0.9
Base Fabrication	WC-M1$^{*}_{1}$	9.0	22.0	(12.5+3.0) × 5	11.625	28.417	Base (I_{121})	0.25	1 × 5	1.25
Front Plate Fabrication	WC-M2$^{*}_{2}$	9.0	22.0	(14.5+2.5) × 5	12.75	31.167	Front Plate (I_{122})	0.32	1 × 5	1.6
Kitting	WC-K1	5.0	8.0	9.0 × 5	3.75	6.0				
Printing	WC-M3	7.0	18.0	3.0 × 2 × 5	3.5	9.0	Dial (I_{112})	0.4	1 × 5	2.0
Kitting	WC-K2	5.0	8.0	2.0 × 2 × 5	1.667	2.667	Label Sticker (I_{12})	0.05	2 × 5	0.5
				Sub Total =	**71.06**	**118.523**				**17.1**
				Totals =			**206.683**			



Aggregate Name	Min_Value	Max_Value
ASSEMBLY_TIME	43000	51000
COST	798.00	815.00

Figure 14. An example of the aggregates.

Table 12. An example of customer order data for the product variant in Tables 9 and 10.

Order #:
CO-01
Customer Info:
xxxxxxxx
Volume:
5
Due Date:
xxxx
Delivery:
xxxx
Description:
xxxx

Functional Requirements:
PaperBox.Type = Delux
LabelSticker.Pattern = HKUST
Hands.SettingType = Three-Hand
Hands.Color = Grey
Hands.Size = Medium
Dial.Pattern = Photo
Dial.Size = Medium
Base.Shape = Round
Base.Material = Acrylic
Base.Color = Transparent
FrontPlate.Shape = Rectangular
FrontPlate.Material = Acrylic
FrontPlate.Color = Transparent
LabelSticker.Pattern = HKUST
Transmission.Alarm = Yes
Core.Alarm = Yes

determined from job data by taking into account the production volume. This value will be passed upwards in the product structure, i.e., to the parent component. The aggregates (see Figure 14 for an example) are updated whenever a parameter value is specified. Aggregates are presented for each generic part to be produced at a work center. Therefore, both maximum and minimum values are obtained. After all variety parameters are instantiated (a product variant is specified), these values will be identical. For a number of different line items, aggregates can also be calculated for each work center in terms of total production time and costs so as to plan the machine capacity.

(4) *Product costing:* Based on the generic BOMO, product costing can be detailed to the production operation level. Table 11 presents the costing data of the product variant defined in Tables 9 and 10. In the table, the labor, overhead and material costs are broken down to operations. For each operation activity, the labor and overhead costs are proportional to its consumption in terms of runtime. The associated runtime can be determined from the production job data (Table 10). Both unit labor and overhead costs are calculated according to a pragmatic approach to product costing based on standard time estimation (Jiao and Tseng, 1999b). Therefore, all runtimes are calculated according to the standard time allocation. Material costs can also be traced to the associated operations according to the operation-material relationship established in the generic BOMO.

The generic BOMO structure is ideally suited to the roll-up technique (as opposed to the cost fold-in technique). During cost build-up processing utilizing the roll-up technique, the appropriate cost elements of lower-level components are added to the calculation of the incremental costs of the parent (the labor and overhead unit costs of the parent). Therefore, the accumulated cost to a specific level is available as well as the incremental costs incurred at a specific level. This provides a basis for work-in-process (WIP) valuation, incorporating labor, overhead and materials values up to the completion of each production operation. It also facilitates the efficient estimation in dollars by work centers or operations in order to monitor the performance of labor and machines.

(5) *Customer order processing:* From a customer perspective, a product should be described in terms of its functional requirements (Suh, 1997). In practice, various functional requirements constitute the product catalog that represents the product offerings of a company for the purpose of customer order entry. The indirect identification of product variant by variety parameters and their values facilitates such a representation of functional variety. Based on the generic BOMO structure, each functional requirement can be described by an instance of the generic item, i.e., {FR} ~ {GenericItem.Parameter = ParameterValue}. Table 12 presents an example of the functional specification of a product variant defined in Tables 9 and 10. Since variety parameters coherently link customer needs to the corresponding BOM data, such a representation of the functional view of product lines, incorporating product costing described earlier, provides a basis for rapid response to request-for-quotation (RFQ) in customer order processing. Through variety parameters, a customer order can also be directly related to the production job data derived from the generic BOMO. Therefore, the generic BOMO performs as a data structure that ties customer orders to their related BOMs and operations routings, thus facilitating the management of customer orders in their production process.

5. Discussion and Future Work

Recognizing the necessity for the unification of traditional BOM and routing data, this research extends the generic BOM concept, which deals with variety, yet focuses on the product structure only, with process considerations. The proposed generic BOMO emphasizes assembly-to-order products for which the major challenges of operations planning lie in the relationships between diverse product variants and the corresponding production process variations as well as the selection of various operations alternatives with respect to a large number of functional requirements and their combinations.

The construction of a generic BOMO is based on a variant, instead of generative, strategy. That is, both the product structure and the operations sequence of all variants are assumed to be common within a product family, thus providing a stable enabler in BOM explosion and operations planning. As a result, the diversity in products and processes only results from different instances of the same product and process structures in terms of variety parameters and their values. Any changes in either product or process structures are regarded as belonging to different product families. Such an implication of variety underlying product families—variant handling—also discerns the generic BOMO from traditional tasks of process planning or assembly planning which concern different individual parts or products instead of families of variant ones.

As might be noticed, the maintenance of explosion and planning rules by enumerating all possible combinations would pose a major problem in practice where a large number of constraints are possible. An on-going project is to tackle the effective management of the explosion and planning processes using the Petri-net technique based on the object-oriented modeling of a generic BOMO.

Considering the ultimate goal of mass customization production, a project of virtual design by customers is also motivated to enhance sales and marketing by linking customer order handling directly to design engineering and production planning. The generic BOMO structure and electronic commerce are the kernel of this investigation.

6. Conclusions

High-variety production like mass customization is facing the challenge of effective variety management. The shortfall of MRPII arises from the fact that production activities related to demand, capacity and materials are planned separately due to unintegrated product and production data. In this paper, a generic BOMO structure is proposed to tackle these problems. A BOMO combines both BOM and routing contents together to reflect the flow of material through the production process. A generic variety structure provides a concise way to characterize variant derivation at different levels of the structure, variety parameters, and/or parameter values. A generic BOMO allows for flexibility in handling relationships between materials and operations in response to diverse customer needs, thus providing a standard data source for synchronizing multiple perspectives on variety in product management and production planning. The consistent use of variety parameters and their values within a single generic BOMO structure facilitates a coherent maintenance of BOM and production job data, which allows the production system to accommodate a wide range of product variability and production variations in practice. The object-oriented modeling of generic BOMO facilitates the identification of product/process variants through instantiation of the generic variety structure, instead of enumerating millions of part numbers. To help customer order entry and management and to improve shop-floor operations efficiency, customer order contents are added to, and traced within, the generic BOMO via certain sets of variety parameter values. A case study for producing a wide variety of customized souvenir clocks demonstrates the feasibility and potential of the generic BOMO methodology.

Acknowledgments

This research is partially supported by Computer Products Asia-Pacific Ltd. (Power Conversion, Hong Kong) under grant CPI 95/96.EG01, the HKUST Research Infrastructure Grant (RI 93/94 EG08), and the Hong Kong Government Research Grant Council (HKUST 797/96E and HKUST 6220/99E). The authors would like to express their sincere thanks to Dr. M. Eugene Merchant, Professors Stephen C.-Y. Lu, Num P. Suh, Gunnar Sohlenius and Martin Helander for their valuable advice. Tilo Geisel, Denil Chan and Shengjun Chen are acknowledged for their help in the groundwork.

References

Bei, Y. and K. J. MacCallum. 1995. “Decision Support for Configuration Management in Product Development,” *Proceedings of the 3rd International Conference on Computer Integrated Manufacturing*, World Scientific, Singapore, Vol. 1, pp. 278–286.

Berger, G. 1987. “Ten Ways MRP Can Defeat You,” *Proceedings of the American Production and Inventory Control Society*, pp. 240–243.

Bertand, J., J. Wortmann and J. Wijngaard. 1990. *Production Control: A Structural and Design Oriented Approach*, Elsevier.

Blackburn, J.H. 1985. “Improve MRP and JIT Compatibility by Combining Routings and Bills of Material,” *Proceedings of the American Production and Inventory Control Society*, pp. 444–447.

Booch, G. 1990. *Object-Oriented Design with Applications*, Benjamin/Cummings, Redwood City.

Chang, S.-H., W.-L. Lee and R.-K. Li. 1997. “Manufacturing Bill-of-Material Planning,” *Production Planning & Control*, Vol. 8, No. 5, pp. 437–50.

Child, P., R. Diederichs, F.H. Sanders and S. Wisniowski. 1991. “SMR Forum: The Management of Complexity,” *Sloan Management Review*, Vol. 33, No. 1, pp. 73–80.

Cox, J.F., J.H. Blackstone and M.S. Spencer. 1992. *API-CS Dictionary*, American Production and Inventory Control Society, Falls Church, VA.

Erens, F. J. and H.M.H. Hegge. 1994. “Manufacturing and Sales Co-ordination for Product Variety,” *International Journal of Production Economics*, Vol. 37, No. 1, pp. 83–99.

Erens, F., A. McKay and S. Bloor. 1994. “Product Modeling Using Multiple Levels of Abstraction Instances as Types,” *Computers in Industry*, Vol. 24, No. 1, pp. 17–28.

Garwood, D. 1988. *Bills of Material: Structured for Excellence*, Dogwood Publishing Co., Marietta, GA.

Harvey-Robson, T. 1992. “Engineering Change Control and World Class Manufacturing,” *DTI Executive Briefings on World Class Manufacturing*, Poole, Plymouth and Bristol.

Hastings, N.A.J. and C.-H. Yeh. 1992. “Bill of Manufacture,” *Production and Inventory Management Journal*, Vol. 33, No. 4, pp. 27–31.

Hegge, H.M.H. 1992. “A Generic Bill-of-Material Processor Using Indirect Identification of Products,” *Production Planning & Control*, Vol. 3, No. 3, pp. 336–42.

Hegge, H.M.H. and J.C. Wortmann. 1991. “Generic Bill-of-Material: A New Product Model,” *International Journal of Production Economics*, Vol. 23, No. 1–3, pp. 117–28.

Jiao, J. and M.M. Tseng. 1999a. “An Information Modeling Framework for Product Families to Support Mass Customization Production,” *Annals of the CIRP*, Vol. 48/1, pp. 93–98, 1999.

Jiao, J. and M.M. Tseng. 1999b. “A Pragmatic Approach to Product Costing Based on Standard Time Estimation,” *International Journal of Operations & Production Management*, Vol. 19, No. 7, pp. 738–755, 1999.

Jiao, J. 1998. “Design for Mass Customization by Developing Product Family Architecture,” Ph.D Thesis, Department of Industrial Engineering & Engineering Management, The Hong Kong University of Science & Technology.

KAPPA-PC®. 1998. *http://www.intellicorp.com/kappa-pc*, IntelliCorp, Inc.

Kneppelt, L.R. 1984. “Product Structuring Considerations for Master Production Scheduling,” *Production & Inventory Management*, Vol. 25, No. 1, pp. 83–99.

Krause, F. L., F. Kimura, T. Kjellberg and S. C.-Y. Lu. 1993. “Product Modeling,” *Annals of the CIRP*, Vol. 42, No. 1, pp. 695–706.

Mather, H. 1986. “MRPII Won’t Schedule the Factory of the Future,” *Proceedings of the American Production and Inventory Control Society Annual Conference*, pp. 495–497.

Mather, H. 1987. *Bills of Materials*, Dow Jones-Irwin, Homewood, IL.

Maull, R., D. Hughes and J. Bennett. 1992. “The Role of the Bill-of-Materials as a CAD/CAPM Interface and the Key Importance of Engineering Change Control,” *Computing & Control Engineering Journal*, Vol. 3, No. 2, pp. 63–70.

McKay, A., F. Erens and M.S. Bloor. 1996. “Relating Product Definition and Product Variety,” *Research in Engineering Design*, Vol. 8, No. 2, pp. 63–80.

Orlicky, J. 1994. *Material Requirements Planning*, McGraw-Hill, New York.

Olsen, K.A., P. Saetre and A. Thorstenson. 1997. “A Procedure-Oriented Generic Bill of Materials,” *Computers and Industrial Engineering*, Vol. 32, No. 1, pp. 29–45.

Olsen, K.A. and P. Saetre. 1997. “Managing Product Variability by Virtual Products,” *International Journal of Production Research*, Vol. 35, No. 8, pp. 2093–107.

Pine, B.J. 1993. *Mass Customization: The New Frontier in Business Competition*, Harvard Business School Press, Boston.

Prasad, B. 1996. *Concurrent Engineering Fundamentals*, Volume I, N.J.: Prentice Hall PTR.

Stonebraker, P.W. 1996. “Restructuring the Bill of Material for Productivity: A Strategic Evaluation of Product Configuration,” *International Journal of Production Economics*, Vol. 45, No. 1–3, pp. 251–60.

Suh, N.P. 1997. “Design of Systems,” *Annals of the CIRP*, Vol. 46, No. 1, pp. 75–80.

Trasiopoulos, I.P. 1996. “On the Unification of Bills of Materials and Routings,” *Computers in Industry*, Vol. 31, No. 3, pp. 293–304.

Tseng, M.M. and J. Jiao. 1996. “Design for Mass Customization,” *Annals of the CIRP*, Vol. 45, No. 1, pp. 153–156.

Yeh, C.-H. 1995. “Production Data Modeling: An Integrated Approach,” *International Journal of Operations & Production Management*, Vol. 15, No. 8, pp. 52–62.

Yeh, C.-H. 1997. “Schedule Based Production,” *International Journal of Production Economics*, Vol. 51, pp. 235–242.

Van Veen, E.A. 1992. *Modeling Product Structures by Generic Bills-of-Materials*, Elsevier, New York.

Van Veen, E.A. and J.C. Wortmann. 1992. “Generative Bill of Material Processing Systems,” *Production Planning & Control*, Vol. 3, No. 3, pp. 314–26.

Wortmannm, J. C., D.R. Muntslag and P.J.M. Timmermans. 1997. *Customer-Driven Manufacturing*, Chapman and Hall, London.

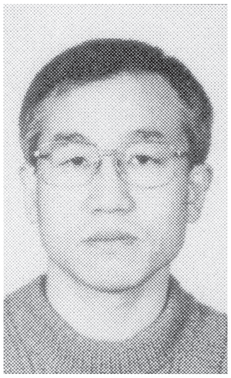
Jianxin Jiao

Dr. Jianxin Jiao is Assistant Professor of Systems and Engineering Management, School of Mechanical and Production Engineering, Nanyang Technological University, Singapore. He received a Ph.D from the Department of Industrial Engineering and Engineering Management, Hong Kong University of Science & Technology. He holds a bachelor’s degree in Mechanical Engineering from Tianjin Institute of Light Industry in China, and a master’s degree in Mechanical Engineering from Tianjin University in China. He has worked as a lecturer in Department of Management at Tianjin University. His research interests include design theory and methodology, manufacturing systems engineering, mass customization, and global manufacturing.

Mitchell M. Tseng

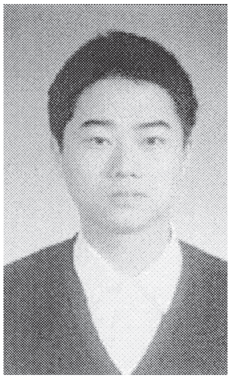
Professor Mitchell M. Tseng is Professor and Head of Department of Industrial Engineering and Engineering Management, Hong Kong University of Science and Technology. He holds a B.S. degree in Nuclear Engineering from the National Tsing Hua University in Taiwan, a M.Sc. degree and a Ph.D in Industrial Engineering from Purdue University. He joined the Hong Kong University of Science and Technology as the founding department head of Industrial Engineering 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.

Qinhai Ma



Dr. Qinhai Ma is Associate Professor of Management and Industrial Engineering, School of Business Administration at Northeastern University, China. He received his B. Eng (1984) and M. Eng (1989) degrees in Management Engineering from Northeastern University, China, and his Ph.D (1999) degree in Industrial Engineering and Engineering Management from Hong Kong University of Science and Technology. His research interests include service systems engineering and management, business process management, product data management, and information system analysis and modeling.

Yi Zou



Yi Zou is currently a PhD student in the Department of Mechanical Engineering at Boston University. He received his B.Eng degree in Industrial Automation from Zhejiang University, China, and his M.Phil degree in Industrial Engineering and Engineering Management from Hong Kong University of Science and Technology. His master's thesis is related to ultra-precision manufacturing systems. His research experience with the Global Manufacturing Research Group at HKUST helps to carry out some research related to integrated product and production data management for mass customization production.