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Engineering and Managing Global Operations

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Mass Customization

Engineering and Managing Global Operations

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Preface

In 2001 in a literature review article on mass customization (MC) published in the *International Journal of Production Economics*[1], the two editors of this book and Denis Borenstein proposed future research directions envisioned as promising in the subject. Most of them were related to engineering aspects of MC which, at that point, were yet to be explored in the literature. We had hit an emerging topic, and the article has received hundreds of citations since then. MC was a promising production strategy in industry, catching the attention of researchers and practitioners.

To date the subject is still receiving great attention in the operations management and industrial engineering literature. The focus, however, has shifted from strategic to operational, and topics such as product development for MC and the scheduling of customized production jobs have been explored. Gradually the research directions we enlisted in the 2001 paper have been addressed through different propositions in the specialized literature.

This book is a compendium of recent engineering and management research on MC. We invited renowned researchers to give contributions on the subject, and the result is a state-of-the-art collection of technical chapters on different, relevant aspects of MC. It covers MC in the context of global industrial economics and operations. The book is divided into four parts, moving from broad strategic issues to operational decisions and case illustrations; 17 contributed chapters are included in the book.

Part I, entitled *Concepts and Definitions*, is comprised of three chapters. Chapter 1, by Roberto Lu and Richard Storch, presents an approach to the analysis of the design, planning, and operation of global MC production systems. To model such systems, the authors use discrete event simulation, statistical modeling, and real option analysis techniques. A literature review covers the state of the art of the use of such tools in MC analysis, and the propositions are illustrated through a case study from the aircraft manufacturing industry.

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[1] da Silveira, G, Borenstein, D, Fogliatto, FS (2001) Mass customization: Literature review and research directions. International J of Production Economics 72: 1–13.

Chapter 2, authored by Rebecca Duray, offers an update on Hayes and Wheelwright's product-process Matrix[2] in order to accommodate MC as a competitive possibility. After providing an overview of the matrix variations proposed in the literature, the author expands the traditional bi-dimensional matrix with product and process structures in the axes to include a third dimension named process variation. The result is a model that incorporates standard process types as well as mass customization. The chapter closes with future research directions of the proposed model.

In Chapter 3, Ian McCarthy, Leyland Pitt, and Pierre Berthon shift the focus from the manufacturing to the services industry and propose a dramaturgy-based strategy to mass customize services. The authors present a typology with four configurations for achieving service customization. Such configurations are obtained by combining levels of two variables: time pressure to customize and level of customization required. Dramaturgy concepts of performance, scripts, and improvisation are analyzed in the light of the four configurations, and ideal settings for each type of service customization are proposed. The chapter closes with a discussion section in which research opportunities on the subject of service customization are identified.

Parts II and III are fully devoted to the engineering of MC and were divided, following the emphases of the contributions, into product and process related analyses of MC in industry. Part II, entitled *Engineering of Mass Customized Products*, is comprised of six chapters. Chapter 4, by Nizar Abdelkafi and Margherita Pero, presents a framework for aligning product development activities and the management of supply chains. The proposed alignment framework explores the relationships between two sets of variables: those related to the product, which are variety, modularity, and innovativeness, and those related to the supply chain, which are configuration, collaboration, and coordination complexities. The framework development was motivated by a case study, which is also presented in the chapter.

Chapter 5 was written by Adrian Mondragon and Christian Mondragon, and is a natural follow-up to the developments in the previous chapter. The authors explore the relationships between MC, modularity, technological innovations and the supply chain. More specifically they discuss the management of technological innovations using modularity to provide customized products. Their propositions are founded on empirical observations of well-succeeded MC cases in the automotive industry.

David Ben-Arieh contributed Chapter 6, discussing the platform based design and production strategy, a recurrent research problem in the MC product design literature. Ben-Arieh presents a linear programming approach to the problem in which the objective is to identify a platform that allows production of a family of products at a minimum cost. Three methodological propositions of the problem are presented, and the developments are illustrated using a simulated example.

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[2] Hayes, R, Wheelwright, SC (1979) Link manufacturing process and product life cycles. Harvard Business Review 57: 133–140.

The development of product platforms for MC is also the subject of Chapter 7 by Sagar Chowdhury and Zahed Siddique. The authors are interested in the development of commonality indices that indicate products belonging to a common family. They propose two families of indices for component shape comparison: dimensional-related and positional-related indices. These two sets of indices are combined to generate platform indices aimed at helping designers in platform decision problems. Two case studies illustrate the proposed indices. The first one deals with a platform for cell phone casings; the second case presents a coffeemaker product platform.

The platform problem in the previous two chapters is extended to the services industry in Chapter 8, written by Seung Moon, Timothy Simpson, Jun Shu, and Soundar Kumara. The authors use a quite innovative approach, relying on data mining techniques to identify a service platform to create a family of service variants. More specifically fuzzy clustering is used to partition service processes generating modules used to create a service family. The developments in the chapter are illustrated in a case study from the banking services industry. A future research section closes the chapter.

Chapter 9 closes Part II of the book. In this chapter Shane Xie presents a STEP (standard for the exchange product model data)-compliant on-line digital library for the rapid development of high value-added customized products. The chapter presents a method to create a product digital library for digitizing customized products. Once available the information in the library will be reused in the development of different customized items. A case study illustrates some of the propositions in the chapter.

Part III congregates six chapters under the title *Engineering of Processes for Mass Customization*. It opens with a review of enabling technologies for planning and control of MC processes, written by Mitchell Tseng and Andreas Radke. The chapter reviews the literature to present the state of the art on propositions to address three subjects that constitute challenges in production planning and control of MC environments: demand forecasting, economies of scale, and product development lead times. The authors review over 100 references to accomplish their objective.

Chapter 11, by Neville Lee and James Dai, investigates a technological aspect of MC production systems: the material handling system (MHS). More specifically the authors review the literature on the design and planning of MHSs for MC, and eventually present the design and planning of a flexible MHS based on the use of free-ranging automated guided vehicle with an indoor local positioned system. A case study from the apparel industry closes the chapter.

Geraint Owen, Jason Matthews, Richard McIntosh, and Steve Culley are the authors of Chapter 12; they propose design for changeover (DFC) as a tool to enable flexible manufacturing of MC products. The DFC methodology is based on the concept of determining the correct interfaces between machine elements that different resources (*e.g.*, personnel, hand tools) must act upon. To achieve that DFC, indices and design rules are proposed and illustrated through a game conceived to train industry's practitioners on the methodology.

In Chapter 13 Phil Reeves, Christopher Tuck, and Richard Hague investigate the applicability of additive manufacturing (AM) in MC production environments. AM, also known as rapid manufacturing, is a denomination for different process technologies such as laser sintering and three-dimensional printing. AM produces components additively by adding successive layers of material together, guided by three-dimensional CAD (computer aided design) data. Thus parts or final products are produced directly from digital data, providing the flexibility desired in MC production. The authors investigate the applicability of AM in the manufacturing of customized items derived from computer games in a case example. They close the chapter by discussing the implications of AM adoption in MC businesses and propose some future research directions.

In Chapter 14, Michel Anzanello investigates the problem of variable selection for clustering of product models into families based on their common processing needs. The objective is to increase the efficiency of production programming and resources allocation through proper clustering of models. To attain this it is crucial that relevant clustering variables be identified, and the author proposes a method for variable selection that integrates an elimination procedure with a *k*-means clustering technique. Some of the clustering variables investigated are related to the worker's learning rate, being modeled through learning curves. Learning is a key element in MC production environments where model changeover is intense and lot sizes are small. The author illustrates his propositions in a case study from the shoe manufacturing industry.

Chapter 15, by Hartanto Wong and Mohamed Naim, closes Part III of the book. The authors analyze the benefits of postponement (also known as delayed product differentiation, a key strategy to attain MC in practice) under a new perspective where the production-inventory and the marketing functions are aligned to maximize profits. They provide mathematical models for manufacturing configurations comprised of different levels of four variables: inventory, lead time, price, and product variety. The authors present the benefits of postponement under each configuration through numerical examples.

Part IV of the book is devoted to contributions in which theoretical propositions are strongly backed by case studies. Two chapters are included in this section of the book. In Chapter 16, Andreas Kaplan introduces the idea of virtual worlds as a means to achieve MC in practice. Virtual worlds encompass Internet-based applications that enable consumers to interact with each other in real time; the virtual social world Second Life, by Linden Research, Inc., is a typical example of such applications. Professor Kaplan states that Second Life offers opportunities for virtual MC and investigates such statement using three case studies in which companies' corporate activities take place in virtual worlds, integrating customers into the production process and thus enabling virtual MC.

Our book closes with Chapter 17, authored by Jason Matthews, Richard McIntosh, and Glen Mullineux, in which the feasibility of MC applications in the food industry is investigated. The authors review the literature on MC applications in industry, list the most prominent techniques used to enable that, and explore their applicability in a series of case studies from the food and beverage industries.

We are grateful to Mateus Dalci who tirelessly helped us to edit this book and to the staff at Springer-London who always provided the assistance to carry out this project. We particularly thank Jaydeep Balakrishnan, Jonas Carvalho, Mohamad Jaber, Elmostafa Qannari, Klaus Schützer, Henrique Rozenfeld, and Cameron Welsh for reviewing initial versions of the book chapters. Finally, we are very grateful to our contributors for giving us such qualified material and for their patient compliance to rules and deadlines throughout the editorial process.

Professor Fogliatto would like to dedicate this book to Prof. Susan L. Albin, with gratefulness and admiration. He would also like to acknowledge the support provided by CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) through research grant 301380/2008-2.

Prof. da Silveira dedicates this edition to his family. He thanks for continuous research support by the Natural Sciences and Engineering Research Council of Canada and by the Warren & Marline Dyer Faculty Fellowship at the Haskayne School of Business.

Good reading!

Porto Allegre, Brazil
August, 2010

Flavio S. Fogliatto
Giovani J.C. da Silveira

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Part I
Mass Customization Contexts

Chapter 1

Designing and Planning for Mass Customization in a Large Scale Global Production System

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Abstract An approach to the analysis of the design, planning, and operation of a global, large scale, mass customization production system is presented. Methods used to perform this analysis include discrete event simulation and statistical analytical modeling techniques. First, a detailed literature survey of the area is presented, followed by a description of the approach and then a short case study.

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[1] Roberto F. Lu is a Technical Fellow in the Boeing Research and Technology of The Boeing Company. He teaches part time in the Department of Industrial and Systems Engineering at the University of Washington as an Affiliate Assistant Professor. His research focuses on decision analysis, discrete event simulation, analytical process optimization, global logistics, large scale production systems integration, lean manufacturing, robotic applications, and mass customization.

[2] Richard Storch is Professor and Chair of Industrial and Systems Engineering at the University of Washington. His research has focused on large assembly manufacturing systems. His work has appeared in journals such as the *International Journal of Production Research* and the *Journal of Ship Production* (of which he serves as an editor). His work was also presented at the Industrial Engineering Research Conference and the International Conference on Computer Applications in Shipbuilding.

Abbreviations

ANOVA	Analysis of variance
DES	Discrete event simulation
DOE	Design of experiments
IFE	In-flight entertainment
MC	Mass customization

1.1 Introduction

Mass customization is likely to be one of the key enabling principles as people improve production effectiveness to meet the ever changing demands on large scale commercial products, such as ocean vessels and commercial airplanes. Global businesses that rely on ocean vessels and commercial airplanes often desire mass produced product prices with mass customized features. Success in designing and planning for mass customization in a large scale global production system is very desirable and yet very challenging to obtain. Researchers and practitioners have been seeking feasible and optimal balances between mass production and mass customization for decades.

A large scale production system often involves multiple tiers of global partners producing major components. In addition to the final system integrator, partners can be categorized into three tiers: tier-1, tier-2, and tier-3. The tier-3 partners are likely to design and produce a similar family of parts that have little or no customization. The tier-2 partners may design and produce slightly customized components. The tier-1 partners most likely will be involved in designing and producing mass customized components, working closely together with the system integrator. Ocean vessels and commercial airplanes have hundreds of thousands of individual processes, or what is commonly referred to as “jobs,” in a large scale global production system among all tiers of partners. Product designs and production plans become exponentially more difficult as the level of customization increases among jobs across tiers of partners. Overall performance of the production system can be influenced by some of the following areas: supply chain efficiency, individual partner productivity, inventory of customized products, integration of product configuration, pull and push combined production, global logistics, rate of customization change of final products, and level of customization among partners of all tiers.

The large scale customized production system may never reach a stable status. Companies may not be able to recover from a failure upon the introduction of a brand new large scale mass customized product such as a commercial airplane or an ocean vessel, because of the huge product development cost. Successful large scale customized programs establish product configuration strategy early and execute design and production of customized components among all partners with consideration of the capabilities and attributes of each partner.

This chapter aims to address an approach to the designing and planning for mass customization in global operations. Methods involved in modeling the system are discrete event simulation, statistical analytical modeling, and real option analyses techniques. The approach described has been utilized in part in the analysis of aircraft production and ship production. The use of these methods can provide improved performance of these complex systems and can aid in decision-making concerning the design and operation of such systems. This chapter will consider the state of the art in this area through a detailed literature survey, then describe how the methods can be utilized, and finally provide one case study.

1.2 Literature Background

Mass customization practitioners in all production systems face similar challenges and risks during the customized product development phases and throughout the production execution time frames (Piller 2007, Pine *et al.* 1993). Trends and types of customization have been spreading across all industries, from t-shirts to shoes and from automobiles to aircraft. Gilmore and Pine (1997) defined four distinct approaches to customization and called them collaborative, adaptive, cosmetic, and transparent. Some of the industry in North America practices build to order (Agrawal *et al.* 2001, Brown and Bessant 2003) with ideas that customization can be managed throughout their supply chain (Heikkila 2002, Du *et al.*, Frutos and Borenstein 2004). Customized product configuration (Jiao and Tseng 2004, Wang and Jiao 2003, Krishnapillai and Zeid 2006) can be important in a global production system (Khouja 2003). An enterprise-wide computing system (Chandra and Kamrani 2003, Karcher and Glander 2003, Gao *et al.* 2003) needs to be in place for managing product knowledge in these systems. In order to model the product decision structure for customized products, a customization index (Fogliatto *et al.* 2003), schedule (Herroelen and Leus 2004) and matrix (Alfieri and Brandimarte 1997) can be required.

In a global organization, the ability to conduct and to model (Roy and Arunachalam 2004) concurrent design and time-to-market of a product (Jiao *et al.* 2004, Sugimura *et al.* 2001, 2003, Kotak *et al.* 2003) can be very important. This includes a holonic view (Cheng *et al.* 2004) of the global stochastic supply chain management system (Hung *et al.* 2004, Blackhurst *et al.* 2004, Lou *et al.* 2004). The ability and methodology to integrate information (Garcia and Dominguez 2004) among entities in a large production system (Bigand *et al.* 2004) needs to be adequate and dynamic (Shunk *et al.* 2003). Interrelationships among key activities (Yoshimura *et al.* 2003, Hartley *et al.* 2004) using modularized architecture (Zhang *et al.* 2005) for workflow management (Lin *et al.* 2004) can be very challenging to model and to analyze (Tseng *et al.* 1998, Fowler and Rose 2004, Bandivadekar *et al.* 2004, Kreipl and Pinedo 2004). A part of this includes consideration of the cost of ownership (Degraeve *et al.* 2005). Levels of product customization depend on product volume and design configurations (Mikkola and

Gassmann 2003, Shah *et al.* 2002). The more mass-produced a product is, the smaller the likelihood of mass-customization. It is important for design teams to explore the customer's perception of the appearance of a target product (Eaves and Kingsman 2004).

Customized product manufacturers may also share some similarities in inventory strategies with hybrid manufacturing and remanufacturing systems that have a long lead time for manufacturing and a short lead time (Chakravarty and Kumar 2002) for remanufacturing in a push and pull (Lu 2006) combined system (Teunter *et al.* 2004). Separate pull in more complex inventory systems (Faaland *et al.* 2004, Johnson and Whang 2002), for instance with stochastic lead time of fast reconfiguration (Villa 2002), may further detail the framework (Brailsford *et al.* 2004) of the global supply chain (Beamon 1998, 1999, 2001, Vachon and Klassen 2002). Logistics support (Cochran and Lewis 2002, Biswas and Narahari 2004, Verbraeck and Versteegt 2001, Lu and Storch 2004) is a key element in the supply chain system of customized systems (Browning and Eppinger 2002). A detailed mass customization literature review (Da Silveira *et al.* 2001) provided a comprehensive guide for researchers at large.

Simulation can be utilized as one of the methodologies in modeling a mass customized large and complex global production system. There are a number of challenges in modeling such a mass customized system. These include (1) applying an object-oriented system-development approach (Hardgrave and Johnson 2003), (2) dynamic modeling (Wikner 2003), (3) using different system classes (Smith 2003) (4) considering resource-driven issues (Schruben and Roeder 2003), (5) considering the product life cycle (Chen and Lin 2004), (6) addressing partnership considerations (Linton 2003, Choi *et al.* 2002), and (7) considering cross-functional team performance (Patrashkova-Volzdoska *et al.* 2003, Kock and Davison 2003). Then the positive link between the use of collaborative technologies and knowledge sharing may offer more positive possibilities in customized product ordering (Jeong and Cho 2006) and manufacturing. Thus, there is a need for unique infrastructures that enable suppliers to perform as partners together with the final system integrators from product configuration (Forza and Salvador 2007) and design (Siddique and Ninan 2006, Mikkola 2007) to product delivery (Xu and Yan 2006). Challenges in managing partner events in a system can be geographical constraints, logistics demands (Lu and Storch 2006), supplier/partner integration from design to delivery, and the synchronization of the delivery schedule across suppliers/partners.

In a large scale production system of mass customized and complicated products, product design is often bounded by basic categories (Kaplan *et al.* 2007) of components from producing partners and global logistics constraints. The use of simulation modeling (Kumar 2007) technology may offer a view of the potential future production system. As for any of the simulation modeling practices, verification and validation (Lu and Storch 2007) analyses are necessary. Production stability of a mass customized production system is often a moving target, which depends on the product and market maturity and the learning rate among all partners (Lu *et al.* 2009). Strategies that are set in the early phases about product configurations and partner alignments will influence the future productivity of any mass customized production system. Hence, the increase in the complexity of analyzing such systems *via* modeling becomes clear.

Dynamic interaction (Lu *et al.* 2007, Vits *et al.* 2006) among partners with respect to different customization levels and the integrator (Storch *et al.* 2007) is one of the important considerations for interim product development and design (Chen and Jin 2006).

The various stages of interim products among different levels are shown rowwise in Table 1.1. Interim product customization complexities decrease as the stages move to lower levels. Interim products at the detail level of large component assemblies may have many different design purposes at that level than at other levels (Fogliatto and Da Silveira 2008). The customization factors at the detail level may consist of variable designs and repeatable sections and substructures. At the component level, basic structure would be the factor to consider since for a given large component assembly, there may exist few predefined basic component structures (Zhang *et al.* 2003). Customization of these basic structures came from already defined subcomponents at the detail level.

Table 1.1 Customization factors (Lu *et al.* 2007)

Stages of interim products		
System level	Component level	Detail level
Large component assemblies	Basic structure	Custom design Repeatable sections Substructures
Propulsion system	Power and efficiency	Thrust providers Additional capacities
…	…	…
Final integration	Interior	Number of classes Floor layouts
	Control systems	Regulation requirements Customer-specific needs

Upon examination of stages of interim products within the same level, as shown in the columns in Table 1.1, the major factors to consider (Blecker and Abdelkafi 2007) at the system level are large component assemblies, the propulsion system, and final integration. As has been briefly described (Zhang *et al.* 2006), no one entity can encompass all activities associated with global large scale customized production. Individual considerations at the system level are based on practical and logical capabilities in existing markets and infrastructures. Technology and product providers in the propulsion business may not have sufficient interest or the means to manage customized large-component assemblies or the final integration. To separate stages of interim products at the component level, one must consider both the detail and the system levels (Jiao *et al.* 2005) in order to maintain the appropriate customized system hierarchy and agility (Zeng *et al.*

2006). For example, large structural components and propulsion system components shall be fully constructed and assembled prior to the final integration stage (Jiang *et al.* 2006). Customization of large structural and propulsion components should be completed prior to the final integration stage as well. The execution of customized control systems and interior features normally happens at the final integration stage. Thus, matched products at the component level of the final integration are interior and control systems. This strategy in categorizing stages of interim products in a mass-customized large scale production system provides the ability to make changes at various stages of the system with minimum disruptions of the final integration schedule (Anzanello and Fogliatto 2007). A digital/virtual factory (Bullinger and Schweizer 2006) for the purpose of realization of the potential and possible production system for a mass customized, complicated product thus becomes a fruitful thought.

Customized product configurations and their respective decision points may vary in different market locations. Optimal opportunities for customized product configurations of large, integrated products such as commercial airplanes and ocean vessels only exist in a narrow window from the product inception to the product design stages (Lu and Storch 2005). During this critical phase of product development (Stummer and Heidenberger 2003), suppliers, designers, and the final integrators share mixed responsibilities based on predicted market trends and customer surveys (Fleischanderl *et al.* 1998). The final customized product integration contains a group of large component assemblies, whose end items are supported by a given number and type of suppliers. All of the small common parts, such as commonly used rivets, can be mass-produced by subsuppliers. There may be multiple tiers of end item suppliers and subsuppliers. Large component assembly is likely to take place simultaneously at multiple geographical locations in a vertical integration scheme (Dedinak *et al.* 2003).

1.3 Methods and Analysis

The traditional manufacturing system ordinarily progresses according to established planning and scheduling. In a supplier-involved dynamic mass-customized system, both pull and push (Lu 2006) will take place alternately and simultaneously as part of the manufacturing and supply chain logistics. From the customized product point of view, end items gather together where large component assembly takes place. Then, the final product integration can be performed by transporting the necessary large components in a timely manner. Most large scale system integrators of customized assemblies strive to minimize the “makespan” during the final product integration stage, while the time between final product deliveries and the final product integration can be much longer and less predictable than the product time resident within the final product integration. Further customization of already assembled products beyond the final product integration can be very unfavorable.

This chapter discusses large-scale production systems with partners located globally. These partners not only share responsibilities in producing mass-customized components, but some of them are also responsible for a part of the product design. The traditional bi-directional information opposite to the product flow type of supply chain system is employed in this system. Figure 1.1 (Lu, *et al.* 2007) outlines a framework of a large scale customized production system. Major production events are categorized as end items logistics (such as one of the wing panels of an airplane), large component (such as the whole wing of an airplane), final production integration (such as a completed airplane), and final production delivery (such as a fully tested and functional airplane certified to fly and to carry passengers/cargo). Customization can take place in any of these major steps and between steps as well.

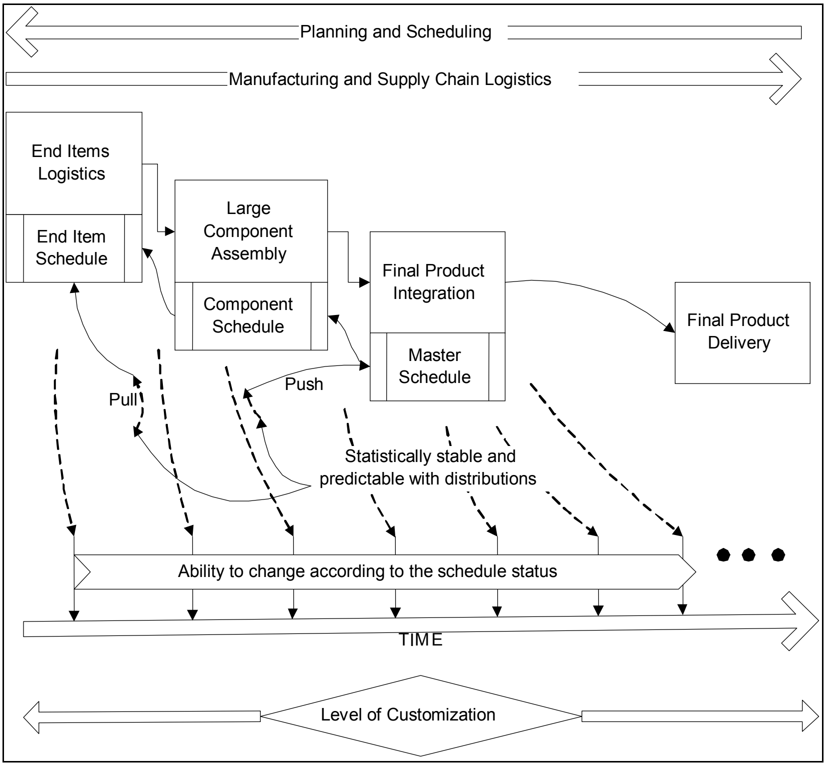

Figure 1.1 System modeling of a customized product supply chain in a large, integrated system (Lu *et al.* 2007)

Most major components in a large scale production system require unusual logistics in the supply chain infrastructure because of their large physical sizes and levels of customization. There are given limited capable suppliers globally that can produce certain large size components, and locations of these suppliers and their available logistics resources vary across the whole system. Most major suppliers in this type of system work together in forms more like partnerships. It has been very common to have more than 60% of the final integrated product value assigned to the responsibilities of the suppliers. The integration of the manufacturing processes and supplier event management are keys to the success of such system integration.

There are many different types of suppliers/partners. Some of them produce the same product over and over, while some of them only make specialized products for certain configuration requirements, and most others are somewhere in between. In this system, three types of suppliers are identified: the type 1 suppliers (S1) provide components of same configurations to the pre-integration location, the type 2 suppliers (S2) provide minor variations of the same component to the pre-integration location, and the type 3 suppliers (S3) provide components of more variations to the final integration site as seen in Figure 1.2.

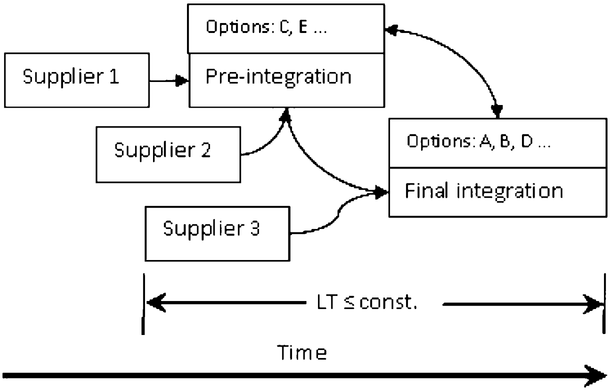

Figure 1.2 Overview of a sample system (Lu and Storch 2005)

Most products made from large production system integration have individually specified customers predetermined many years and/or months prior to product final integration and delivery. Demand forecasts throughout all configurable levels in this system normally are not easily or accurately developed. However, such forecasts are necessary to plan supplier related events. Customers prefer that product configurations be finalized as late as possible. On the other hand, the system integrator and suppliers prefer finalized configurations as early as possible. In an actual system, some configurations are common throughout all product lines and some customized configurations are to be determined at a shorter lead-time prior to the final product delivery. S1 type suppliers do not handle variable configurations, hence, S1 type suppliers can stock up at a level deemed practical for business execution. S2 type suppliers provide mostly fixed variations for certain customers that do not vary every time. S3 type suppliers only provide customer and product specific configurations directly to the final integration site. Lead times of S3 type suppliers are critical to customers who wish to make final product configurations at the latest possible stage of the product integration stream. Figure 1.2 (Lu *et al.* 2007) illustrates a brief overview of this example system.

Consumer commodity type products that can be acquired from multiple sources normally do not require customized design or a special production system infrastructure. Interfaces for most of the commodity consumer products have already been configured and commonly accepted. Customized products that require electrical and mechanical continuities between sections that come from different suppliers will need a different level of integration throughout the product development and launch phases. There are benefits when suppliers and partners participate in the product design and launch from the early phases of new product development.

For a customized product that takes a few years to design and more than one year to produce and integrate, it is important for suppliers to be involved in the early stages of customized product design and testing cohesively with the pre-integration and the final integration parties. Sometimes, key customers are involved in major product configuration definitions. Thus, all partners concurrently progress through phases of a product launch process.

The benefits of orchestrating such a horizontally and vertically integrated production system with major customers, suppliers, and partners engaged from the very early stage include risk sharing and a faster product launch for the next derivative of the same product family. Suppliers will most likely have guaranteed future businesses for the given unique component for the life of the final product, which normally last more than 30 years. However, the final system integrator is supposedly capable of producing most of the components if it chooses to do so. Because components do not have the same level of complexity, not all suppliers/partners improve through the component manufacturing phases at the same rate. A tremendous amount of learning takes place (Lu, *et al.* 2009) when the final system integrator is designing, testing, and inventing product and process characteristics. When suppliers and partners share risk and benefits in the whole system, all suppliers/partners throughout the supply chain need to learn together and improve processes together.

Commonly known practices can be used to address the fundamentals of the system. These practices may generate, but are not limited to: value stream mapping, network diagrams, use case diagrams, activity diagrams, and Gantt charts. This fundamental work can be utilized to enable more analytical methods, such as discrete event simulation, statistical modeling, and real option analysis technique with Monte Carlo capabilities.

Discrete event simulation methods can be used to encompass the whole production system among all major partners across multiple tiers. The simulated time clock in the model is one of the most essential factors in using the discrete event simulation method. One or more models can be established to run multiple iterations against different product customization levels. Their respective portions and simulated performance of the production system during the product design and planning phases can then be yielded. Several pairs of sensitivity analyses among mentioned influential areas may provide another view of different design and plan strategies.

Since every component has its own serial number attached as an attribute, each component is created individually in step 1, as can be seen in Figure 1.3. The mass customization parameters are then assigned with the same component in step 2. External master schedule data can come from different formats; thousands of data points can be normalized and organized in a spreadsheet and then be read in during step 3. Step 4 then groups all of the component master schedule data individually for the whole simulation duration. Step 5 releases the production order according to the master schedule to each component process accordingly. Before the production order reaches any of the processes, serial numbers are assigned *per* component as in step 6. Step 7 receives the production order and then starts the process within their individual statistical process distribution. Steps 8 and 9 check for mass customization changes; if a change occurs in the system for the first time, then step 11 will take place. Step 12 manages the duration of the change. At the end of the current change, step 10 resets the change variable. Step 13 runs the process. Step 14 can record many different simulation results. Step 15 monitors whether the simulation stop condition has been met or not.

There are several statistical methods that can be applied to analyze the designing and planning of a mass customized family of large scale products. Linear regression, design of experiments (DOE) and analysis of variance (ANOVA) can be applied to analyze product and process factors that matter more than others during the product configuration stages. Statistical methods can also be used to verify discrete event simulation models.

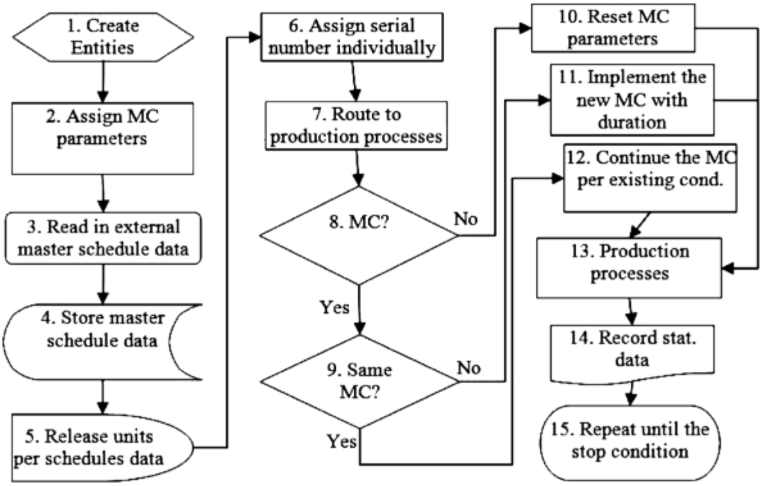

Figure 1.3 Modeling an MC system using discrete event simulation (Lu and Storch 2005)

A verification and validation process is outlined in Figure 1.4, where steps 1 through 5 are commonly used statistical and discrete event simulation (DES) methods. Steps 6 through 10 are main steps used for result validation and verification. The verification of the DES method is performed in step 6, which compares interim statistical and DES findings. The analytical statistical method calculates process durations for all units of all components in a spreadsheet or by using a calculator. The DES method calculates process durations dynamically as each entity passes through their process modules. The process duration is calculated for each component unit only when its representative entity is in the process module. The verification of the DES method is conducted by verifying component unit process times in the DES model against their equivalent component units in the analytical statistical method.

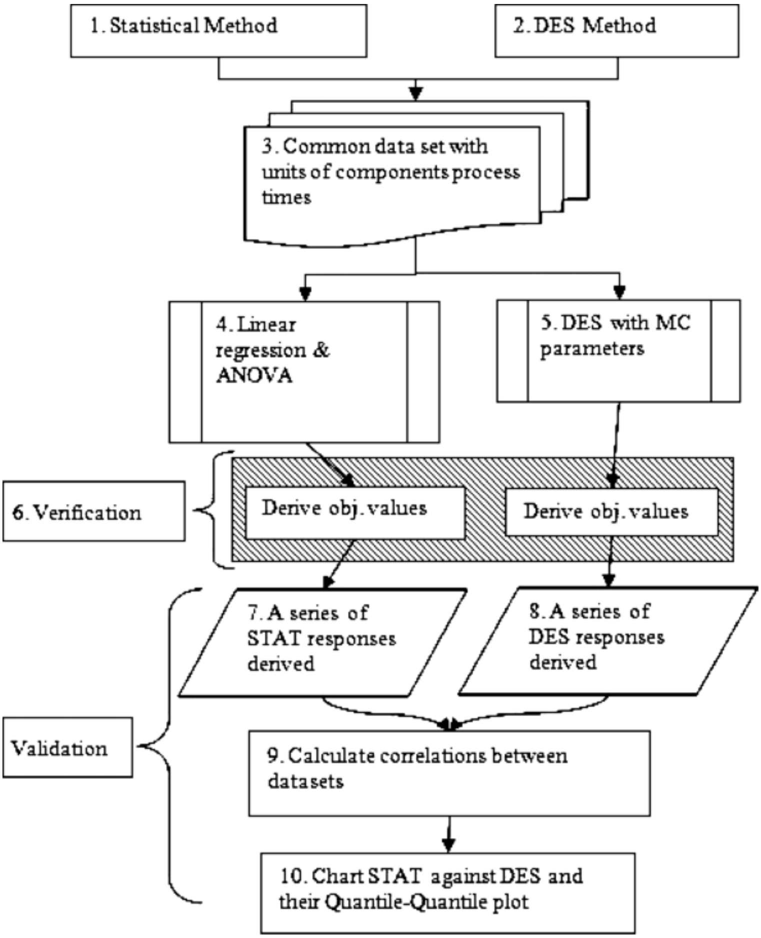

Figure 1.4 Statistical and discrete event simulation method verification and validation

Once MC featured component unit process times are verified, the validation of the DES result can start, beginning at step 7. The ideal validation is to validate the DES modeled system with the real world system. Since the real world system data often is not readily available, the analytical statistical method is applied to validate results from the DES method. Steps 7 and 8 derive the system response *via* statistical and DES methods, respectively. The statistical method calculates MC component unit arrival times in a spreadsheet. The DES method captures MC component unit arrival times at the very moment that each unit has reached its component process line "record" module, which records parameters of entities in a DES model. The DES result is captured during each simulation run near the end of the simulation model. Once statistical and DES versions of the system responses have been collected, the DES result can be validated by the following two steps. In step 9, correlations are calculated using results from both methods. In this approach, the correlation between the two methods is calculated using a Pearson correlation coefficient. The correlation result of both methods will be between -1 and 1. If the value of the coefficient is in the positive range of 0.9 or higher, then there is assumed to be a strong correlation between the statistical and DES methods. Hence, one may use the verified and validated DES method to further employ this MC modeling technique for different hypotheses. Step 10 plots the quantile–quantile plot of the correlation of DES and statistical methods. For a high percentage correlation, the quantile–quantile plot shall show data points following a straight line diagonally across the graph with the slope value close to +1.

The real option analysis technique with Monte Carlo capabilities complements both of the above methods. The real option method does not necessarily need to have a simulation time as a factor in the system. However, the real option technique can have financial aspects of the system in the model. Different customized configurations among different tiers of partners may have different financial influences to the large scale global production system. The time value of technology insertion into different partner tiers for different levels of future production gain and/or product value return can be analyzed using the real option method.

The objective in combining individual processes into groups of product portfolios is to seek the overall optimum system portfolio for manufacturing (Figure 1.5). Customers can have many desired configurations that can be collected in a customized option database. In most production systems, there is a time delay between customized product ordering and manufacturing. The bigger the production system and the more complex the final product, the greater the time delay. Dell computers and Boeing commercial airplanes are two extreme examples. In order to minimize such delay times, an ideal optimum portfolio of customized products is needed for manufacturing facilities to be able to produce customized products.

Advanced knowledge of customization from the manufacturing facility point of view can be very beneficial for production planning. By the same token, accurate forecasts of the production system for future customized product demands can be equally beneficial to the overall mass customized production system.

One of the application cases is based on a new commercial airplane designing and planning process for a large scale global production system. Mass customization of this new commercial airplane is categorized into three main configuration levels. Partners of different tiers and within the same tier participate in the customized designing and planning process very differently. All of the three methods described in the previous section are applicable in the case study.

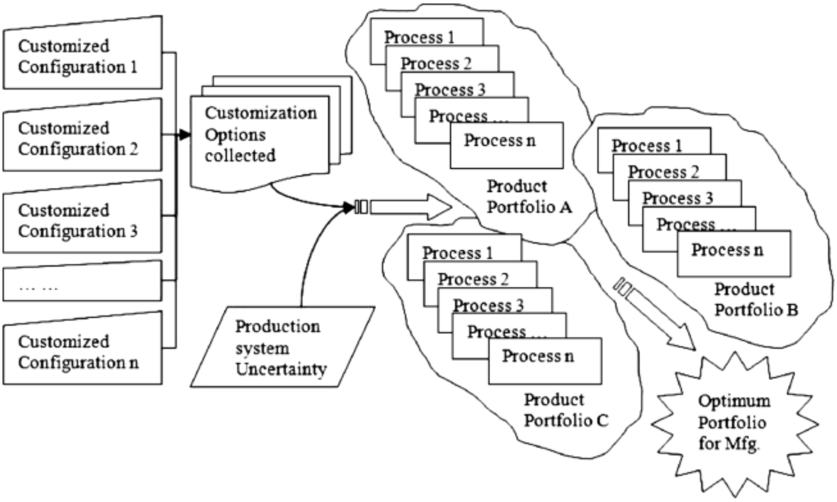

Figure 1.5 Customized configuration to optimum product portfolio for manufacturing

The system in this chapter produces products only if there are customers who have already committed to the purchase. All major components of each product have to be traceable to their source of origin. This type of system is needed for products such as commercial aircraft that involve many suppliers and different components. There are two types of suppliers in this large scale manufacturing system: mass-production producers and customized producers. The mass production suppliers produce the same items over and over, items such as common structural parts, brackets, nuts and bolts, *etc*. The customized product suppliers fabricate products with a set of given customization attributes *per* selections chosen by the final product customer before and/or during different production stages.

The nature of the customization in this study, however, can be categorized into three different types:

1. The fixed optional component. This type of component has one attribute: to be installed or not. If yes, it will be a straight plug-in. An example is whether or not to have a forward cargo air conditioning system in a commercial airplane.
2. A configurable optional component. This type of component has multiple attributes. Further configuration has to be performed before production and installation of such components can take place. A common example is the in-flight entertainment (IFE) system in a commercial airplane. Each airline has different configurations of their IFE for different routes.
3. A retro-fit optional component. This type of component has almost unlimited attributes. Most of this type of components are totally customized and installed after the main product has been mostly finished. An example of such components is the interior of a private business jet.

In a global mass customized production system there are six major events: fabrication starting time, sales commitment, customer introduction lead-time, roll-out from factory, nominal delivery, and target delivery. Figure 1.6 depicts these major events in a mass customized production system in its early stages before the system is stabilized. The *x*-axis is time and the *y*-axis represents the production counts, or the product serial numbers. There are six curves in this diagram. The start part fab curve represents the starting time of component fabrication. Since many components are customized, the trigger to initiate the start production of customized components is critical in the production system. Components that are not customized may start their production prior to firm sales commitments. Components that are customized must wait for the customer to finish the customized configuration before production can start. Therefore, some portion of the start part fab curve is ahead of the sales commitment curve.

The sales commitment curve indicates that the respective sale has been confirmed and committed. In a normal business environment, a sizable deposit would have been transferred from the customer to the manufacturer at the sales commitment. The roll-out from factory curve indicates that production has completed according to the customized configuration. This is different from the delivery time, since in early stages of a new customized product, significant amount of time will be needed for product testing and certification. The nominal time between roll-out and delivery is the gap between these two respective curves. However, the target delivery is much closer to the real product delivery time, which is almost always later than the nominal delivery time. The time between the real delivery time and the time when the customer has completed specifications of all customized configurations is one of the key performance metrics that many MC producers strive to improve.

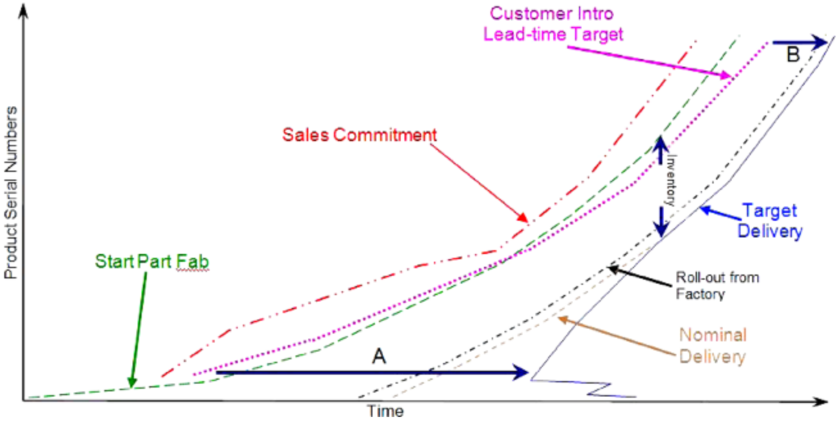

Figure 1.6 Major event relationships in a large scale production system

The customer introduction lead-time target curve represents time delay between customized configuration specification completion time and the respective product delivery time. If a product is from a customer ordering the first one of its kind in a family of products, the product can be referred as a “customer intro” product. In early stages of a new product launch, low product serial numbers in the *y*-axis in Figure 1.6, the time it takes from a customer intro to the product delivery can be much longer than later in the production stages when the system is more stable at higher serial numbers. This is illustrated by the time difference between A and B in Figure 1.6. It is always a benefit to both the customers and the product manufacturers to shorten the customer introduction lead-time. The inventory in this type of production system can be seen as the vertical space between the start part fab and the target delivery curves. As the production system progressing to a more stabilized condition, the inventory level is likely to reduce. Meanwhile, the production rate may rise accordingly to capture potential markets.

The following list of system components are of interest to the system integrators in a global mass customized production system:

1. the final product;
2. integrated components;
3. major structure components;
4. customer furnished components;
5. assembled components;
6. detailed components;
7. system components;
8. plug-and-play components; and
9. custom made components.

Processes that matter in this production system would be the timing of the customized configuration through phases of production, major component design, minor component design, transportation logistics, assembly sequences, work package definitions, due-date criteria, customization criteria, and component ordering system.

System entities are produced by companies categorized by their functional responsibilities. All of them operate according to the general direction set by the final system integrator. However, they are not likely to have the same performance priority individually. System entities regarded in this system are:

1. Detail part manufacturers without customization. They produce the same part routinely until there is a minor model introduction and/or product revision change.
2. Component producers without customization. They assemble sub-assemblies by using non-customized detail parts.
3. Component integrators with customization. They integrate components together with customization. They are also involved in the design processes.
4. Major work package integrators with customization. Their role is similar to the above except they handle more complicated work packages, which are composed of integrated components.
5. The overall final integrator with customization. They are the ultimately responsible entity who integrates all work packages together with customized features.

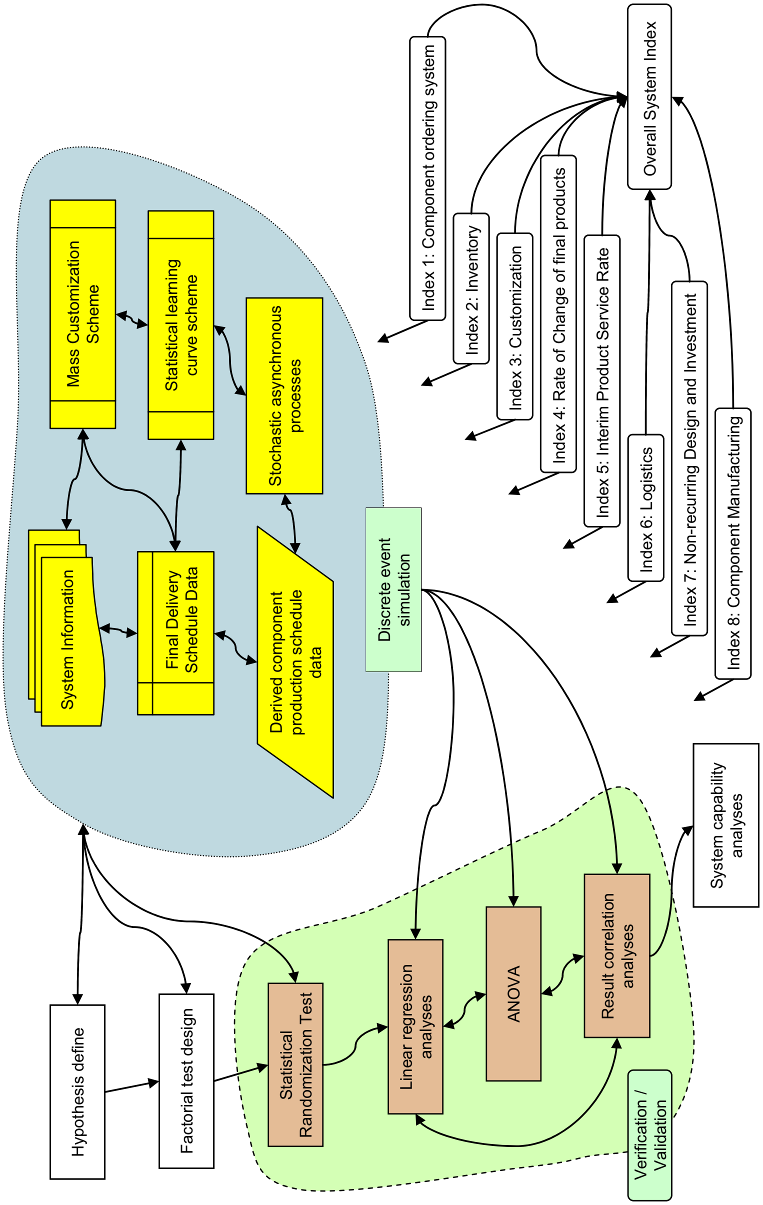

Figure 1.7 Research approach methods

There many unique characteristics in this system; for example, all partners/ suppliers are solo suppliers without any backup sources, almost none of the suppliers have the same lead-time, and almost all produced components are to be integrated to the final product. Each entity in the system possesses the learning/improvement curve characteristics. All suppliers in this system handle more complicated tasks that require more product precision than those producing most ordinary mass-produced consumer type products. The latter would neither have the technology nor the resources to manage operations within the large manufacturing integration arena. It is not implied that all entities can only perform complicated large scale manufacturing tasks without a fair level of effort, especially during early stages of new product launch. Consequently, the rate of improvement for each supplier is a critical system characteristic that can deeply influence overall system efficiencies.

Analytical methods presented in this chapter (Figure 1.7) can be applied to mass-customized large scale integrated production systems. They include a combination of discrete event simulation and statistical methods. Input and output data are handled through spreadsheets and/or plain text files. An off-the-shelf-software package serves as the discrete event simulation engine to model the system events with respect to time sensitive activities. Some of the statistical analyses can be performed using statistical packages. As outlined in Figure 1.7, this approach is to model the whole system in a series of several discrete events. Hypotheses are simulated *via* design of experiments methods followed by statistical randomization tests, linear regressions, ANOVA, and correlation analyses. All of these are simulated with respect to the customization configurations. This methodology is to derive analytical heuristics to analyze and to present the overall system view of a mass customized product.

In a mass customized global production system, these are some of the key considerations concerning detail modeling of the system.

1. All customer intro type customized processes improve their process duration according to their forecasted respective learning curve rates.
2. All stabilized processes stop their learning curve related improvements after a predetermined product serial number has been produced.
3. Interruptions to the system can happen in forms of new product introduction, transportation device failures, and/or process failures.
4. Process starting times have no delay from the ordering trigger times.
5. The percent of customized options is forecasted deterministically in three major categories.
6. All major components join and assembly are from the same serial number subcomponents.
7. A fixed number of modified large cargo freighters are needed to transport a group of components and there is no other alternative.
8. All modes of logistics have no custom delays at all sea and air ports.
9. There is no component build-ahead without an approved final customer. All parts produced will be delivered to and/or assembled at the final integration facility.
10. Most customization work can only be performed one-step prior or one-step after the final integration processes.
11. There are given numbers, *e.g.*, three, of opportunities to define the product customization attributes throughout the whole production time-span, in addi-

tion to the traditional method of fully defined customization attributes prior to the start of production.

12. Component process times are non-negative triangularly distributed on their respectively unique learning curves.
13. Transportation vehicles are allowed to have unscheduled repair performed at the location where unexpected failures happened.

1.4 Case Study

In this case study, real data has been non-dimensionalized for public publication purposes. Production planning data is stored in an Excel spreadsheet. Simulation models read input variables from the workbook and write process results to the spreadsheet. Statistical analysis uses a different spreadsheet that contains randomization processes. Randomized processes in the statistical analysis are to duplicate processes in the simulation model without using a simulation engine or software. Thus, the simulation and statistical methods outlined in Figure 1.4 can be exercised independently for data validation purposes. The high level data structure is outlined in Figure 1.8.

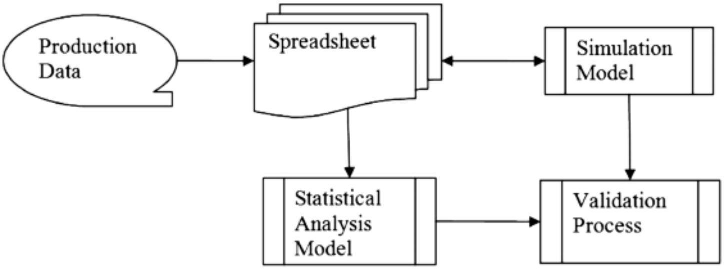

Figure 1.8 High level data structure

In the simulation model, data is processed in the following sequence:

1. Create entities that represent mass customized components.
2. Assign unique serial numbers to each created entities. All customized components start their serial numbers simultaneously from number 1; even if they have different production time and creating intervals. This is an important step, since different components with the same serial number will eventually come together to form a completed product.
3. Read in production schedule from the external spreadsheet. Theoretically, production data can be embedded inside the simulation model. Practically, it will be very difficult to update data value from the production system.
4. Delay the release of customized entities individually *per* component *per* entity in the model *per* the production schedule data read from the spreadsheet.

5. Write the entity release time back to the spreadsheet right after the release of each entity. This is to record the production starting time. In practice, this is the time a mass customized component enters its production system. If we use three different entities for three different customized components, then we will have three columns of component starting time data in the spreadsheet.
6. Route each entity to its respective customized process.
7. Process each customized entity in parallel for different components *per* their individual learning curves and serial numbers. Detailed algorithm in this process is depicted by Lu *et al.* (2009).
8. Write the time to spreadsheet as soon as each entity has finished its customized process. This is the time that represents the entity exiting the production system. If we use three different entities for three different customized components, then we will have three columns of component finish time data in the spreadsheet.
9. Calculate the time difference between steps 5 and 8 in the spreadsheet to yield the individual component process time in the spreadsheet.
10. The longest process time among all components or the latest finished component time is the earliest starting time of the final assembly of all components. Thus the product finish time can be calculated after customized component production times are realized.

The statistical method does all of the calculations in a spreadsheet using very basic formulas with random number generated by Excel, since there are two random number generators, one in the simulation model and one in the spreadsheet. Results from the simulation model and the spreadsheet will not be identical from the same production starting point (see Table 1.2).

Table 1.2 Simulation and statistical methods – data comparison

Simulation	Statistical
25.64	18.93287
20.72	29.61609
13.97	28.34129
13.78	26.73362
8.46	33.27387
15.57	19.59597
20.13	26.55516
23.84	28.65542
9.27	35.92829
16.32	18.35465
…	…

Figure 1.9 depicts results from three different conditions. The N_Stat 0% data line represents the assembly completion time when there is no customization. The trend of the data generally shows trend of a learning curve (Lu *et al.* 2008, 2009). The N_DES 15% and N_Stat 15% data lines represent simulation and statistical

methods in modeling up to 15% customized component processes, respectively. Given that there are some overlapped process times among the three data lines, generally, one may observe the general trend of a learning curve effect. The 15% customization affects process times much greater than the learning curve effects. One may argue if the customization can be done in the best possible fashion, *i.e.*, looking at the lower points along the 15% curves, production time variations can be more manageable. Practically, this will be the ideal state all mass customized manufacturers are striving to achieve.

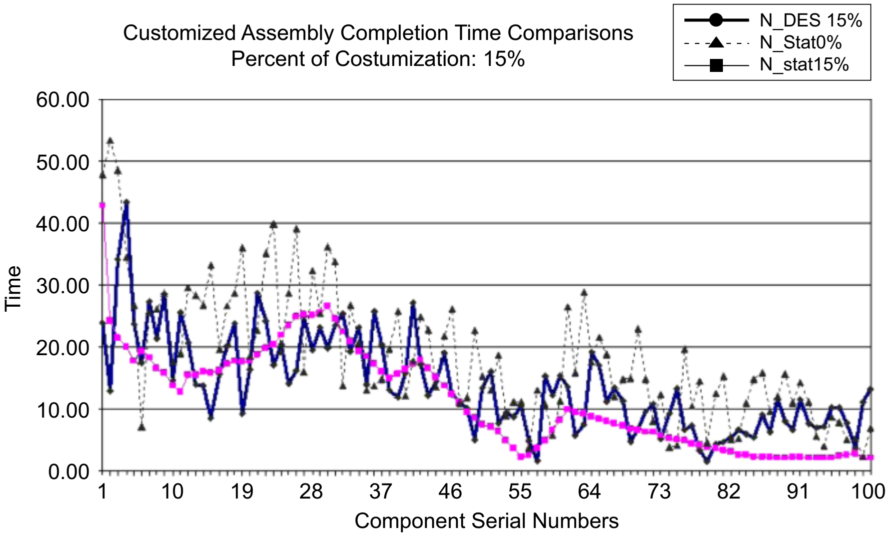

Figure 1.9 Process completion time comparison between two methods

1.5 Conclusion

Advanced methodologies are required to model a mass customized production system, such as for an ocean vessel or a commercial airplane. In such a large scale global production system, not only are benefits from this type of analysis found in the production readiness of the system, but also by providing a means to analyze business strategies from the designing and planning phases to the production execution phases where all partners are consistently being challenged to work in synchronized takt times.

This chapter outlines a framework and attributes of a mass customized large scale production system and methodologies that can be used in addressing key characteristics of such systems. Among these methodologies are discrete event simulation and statistical analytical modeling techniques. For a successful mass customization production system analysis for aircraft and/or ocean vessels, modeling validations are likely to be seen in later years when the system is in a more stable state. For initial system design and start-up, the use of these methods will provide a better way to analyze, design, and control the system and to synchronize operations between partners.

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Chapter 2
Process Typology of Mass Customizers

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Abstract Traditional manufacturing practices required a choice between providing low cost products with mass production or custom products with craft manufacturing methods. Mass customization resolved this trade-off by providing both low cost and customization. Today, mass customization is no longer a new phenomenon but a realistic strategic choice for many manufacturers. As mass customization becomes more commonplace in practice, academia needs to update the traditional models to incorporate this new competitive form. This chapter takes a look at the traditional process tradeoff models and develops a new process model to incorporate the practice of mass customization.

2.1 Introduction

Mass customization had been in practice for many years before academics tried to decipher its components. To some degree, mass customization evolved from traditional manufacturing practices as manufacturers addressed changing customer requirements. Mass customization is emerged in both custom and standard product manufacturers (Duray 2002). For purely custom products, competitive pressure, worldwide markets, and changing consumer behavior pushed manufacturers to reduce costs. The value equation for traditional custom products, such as tailored suits and custom designed furniture, no longer favored providing infinite variety. Custom product producers began to lower their cost structures by either providing less variety or adding commonality among their end items, thereby reducing inventory requirements, cost and/or lead times. For example, some custom shirt tailors

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began to offer limited or more static designs in a few select popular styles with limited fabric choices at lower price points. Cost savings were found with economies of scale in purchasing fabrics and increased volume of certain styles and lead times were shortened with only selected materials readily available to customers. These custom tailors may have lamented the good old days of true customization, but they probably did not label their changes as "mass customization." Rather, these changes were the methods employed to stay competitive with savvy customers requiring reduced prices and quicker delivery. As a counter point, standard product manufacturers were hit with similar competitive pressures of lower cost substitutes. In this type of marketplace, companies often look to differentiate their products. Some standard product manufacturers may have offered mass customization as a means to satisfy customer demand and/or gain customer loyalty. In the early 1990s, Levi Strauss was an early entrant into mass customization in the United States, offering custom jeans at Levi's stores. Levi offered jeans to women only because research showed that women had a more difficult time finding jeans that fit. This is an early example of a standard product manufacturer developing a much publicized mass customization capability. Mass customization is no longer a new phenomenon but a realistic strategic choice for many manufacturers.

Academics have been interested in mass customization since Stan Davis coined the term in his 1987 book *Future Perfect.* Academics in both business and engineering have explored the design, marketing, manufacturing, technology, and information systems requirements of mass customization. Abundant research exists on the practice of mass customization, yet academics have not incorporated mass customization into some of the basic process models used in operations education. The traditional process models are based on Hayes and Wheelwright's (1979) product process matrix. This groundbreaking typology showed the interaction of marketing and operations and highlighted the need for coordination between these two functions. Mass customization is a good example of the marketing manufacturing interface, but it does not fit in this process typology. If mass customization is becoming more commonplace in practice, then academia needs new models to incorporate new competitive forms. This chapter takes a look at the traditional process tradeoff models and develops a new volume-variety-variation process model to incorporate the practice of mass customization.

2.2 Mass Customization and the Product Process Matrix

2.2.1 Defining the Product Process Matrix

In 1979, Hayes and Wheelwright introduced the product process matrix; a framework for mapping product structure with process structure (see Figure 2.1). This revolutionary model defined the concept of a process lifecycle where "the process evolution typically begins with a 'fluid' process–one that is highly flexible, but not very cost efficient–and proceeds towards increasing standardization, mechanization and automation". This process life cycle represents the growth and development of a product, a company, or an entire industry through four stages: jumbled flow (job shop), disconnected line flow (batch), connected line flow (assembly line), and continuous flow. The inherent process trade-off between flexibility (which provides variety) and low cost (achieved by economies of scale with high volume) are explicitly stated.

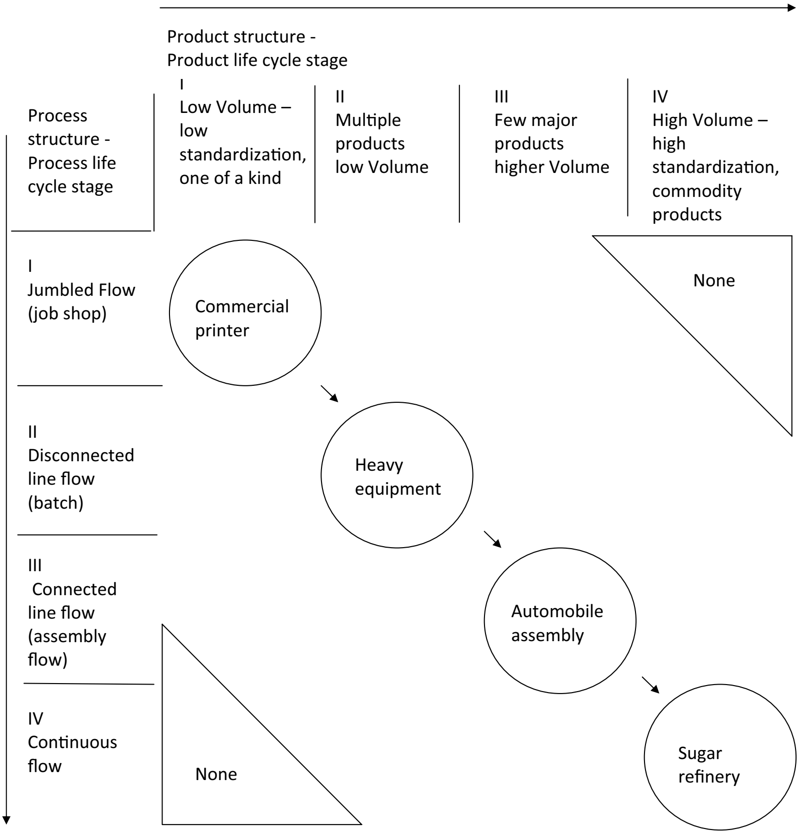

Figure 2.1 Product process matrix (Hayes and Wheelright 1979). Reprinted by permission of Harvard Business Review

The matrix is constructed by mapping the rows to represent the major stages of process evolution from fluid to systematic, while the columns represent product life cycles from large product variety of startups to standardized commodity products. Examples are used to define the intersection of each of these stages on the diagonal; examples show commercial printers, heavy equipment manufacturers, automobile assembly, and sugar refineries. Hayes and Wheelwright further developed this concept in their 1984 book, *Restoring Our Competitive Edge: Competing Through Manufacturing.*

The product process matrix became the cornerstone of process definition. Numerous introductory operations management textbooks include this model (Jacob *et al.*, 2009; Krajewski *et al.* 2007; Schroeder, 2007; Stevenson, 2009). The product process matrix defines the parameters of manufacturing processes in all of these texts. In addition, this matrix provides the foundation for most discussions of operations strategy.

Although the matrix is widely accepted, many textbooks alter the model to better define the process types. The model suffers from two weaknesses. First, the example companies are from different industries. This implies that positions are characterized by specific traditional processes types, when in reality companies in the same industry can compete from different positions on the matrix. For example, cookies can be mass produced on assembly lines and sold through supermarket chains or they can be made by the local bakery in a small batch operation. Using one product across process types better illustrates that that process type is a strategic choice. Hayes and Wheelwright (1979) use the product and process life cycle intersection on the diagonal to show the strategic alignment of operations and marketing strategies.

Secondly, the product life cycle incorporates both volume and variety dimensions that define the exact position of the major process archetypes. Stevenson (2009, p. 231) renames the axes volume and variety with little alteration on the specific definitions. The *X* axis incorporates the concept of volume while the *Y* axis represents variety through the specific product types of job shop, batch, repetitive and continuous. Although this model strips down the axes to volume and variety, their definitions are still incomplete. Variety is represented by process type not by a defined product line breadth and therefore, process type is a poor representation of variety. Although it is true that processes are distinguished by the flexibility in producing product, process types are also defined by the volume that they can accommodate. Stevenson (2009) uses industries, although different industries, for the diagonal examples of processes. This adaptation of the product process matrix does not appear to increase the clarity of the descriptions.

Jacobs *et al.* (2009, p. 207) alter the matrix using standardization and product volume as the axes. Their spectrum of standardization flows from “low – one of a kind” to “high – standardized commodity”, which is the definition of the product life cycle. Therefore, Jacobs *et al.* (2009) follow the traditional definition of the *X* and *Y* axes. However, their model adds “work center” to replace the traditional “job shop” and “manufacturing cells” as the central “batch.” Both the Stevenson (2009) and Jacobs *et al.* (2009) examples show that many authors have tried to expand upon the original concept for clarity in presentation and to accept more forms of manufacturing used in practice.

Krajewski *et al.* (2007 p. 129) use an adaptation of the product process matrix that places process types on the diagonal and uses product design as the *X* axis and process characteristics as the *Y* axis. The process types replace the industry examples, but basically this matrix duplicates the *Y* axis on the diagonal. The list of process characteristics is the same as the definitions of the processes types used on the diagonal. However, when teaching the concepts of process choice, the accompanying video of King Sooper relies on the volume-variety tradeoff to define the process types, *i.e.*, process choice decisions are based on volume and variety. High volume bread is produced on a dedicated line, numerous pastries, rolls, and coffee cakes are produced in a linear flow, batch process, while custom decorated cakes are produced in a job shop. All processes types are located in the same facility. This concept of volume and variety better illustrate the inherent trade-off in processes, but rarely appears in the operations management textbooks. For example, not all automobiles are produced on a traditional assembly line. Automobiles can be produced as project, job shop, batch, or line depending on the volume and variety. While major auto manufacturers use line processes, Tesla electric sports cars prototypes are produced as projects (http://www.teslamotors.com/media/press_room.php?id=1380) and Morgan Motors (http://www.morgan-motor.co.uk/production/index.html) produces its Roadsters in a batch process. Process choice is not industry dependent, but it should be based on the volume and variety of the products.

A summary of the variations on Hayes and Wheelwright's (1979) product process matrix presented in this section is given in Table 2.1.

Table 2.1 Summary of variations of the product process matrix

Source	Hayes and Wheelwright (1979)	Stevenson (2009)	Jacobs *et al.* (2009)	Krajewski *et al.* (2007)
X axis		Volume	Standardization	Product design
Y axis	Process structure	Variety	Product volume	Process characteristics
Diagonal	Industry types	Industry types	Process type	Process type

2.2.2 Strategy of the Diagonal

Hayes and Wheelwright (1979) only considered as appropriate the process configurations located on the matrix diagonal. In the original diagram, the corners of the matrix are void. The authors state that the lower left-hand corner represents a one-of-kind product that is made by continuous or very specific processes. They state that such processes are simply too inflexible for unique product requirements. Using the traditional definition of process types of line and continuous, this premise holds true. Highly mechanized, high volume line processes are designed for specific repetitive tasks and are not designed for flexibility. The upper right-hand corner is characterized by a job shop that provides commodity products. Hayes and Wheelwright state that no companies or industries are in this void. But in practice, mass customizers operate in both of the voids. By definition, mass customization provides one-of-a-kind products at low cost. Hayes and Wheelwright propose that "void" positions are not economically feasible. Producing commodities in a job shop will not be competitive with the low cost and consistent quality of commodities produced in automated line processes. But mass customization could be characterized as “unique products” (job shop) and “large quantity” (commodity). However, mass customized products fall in the other “void” area; one-of-a-kind products made by dedicated processes. With mass customization, most products exhibit some degree of modularity. There is often a portion of the product that is mass produced and used in all products, although each end item is custom designed to a customer’s specifications.

Hayes and Wheelwright do allow for “off diagonal” strategies although they caution companies not to drift off the diagonal position. They acknowledge that successful companies make a deliberate decision to move off the diagonal. They advise that changes in product volume or mix can both have a negative impact on profitability. Off-diagonal positions should be specifically intended strategies such as Rolls-Royce Ltd. producing a limited product line in a job shop. Hayes and Wheelwright do not offer any examples of the opposite void where mass customized production would most likely occur, perhaps implying that mass customization is not possible.

2.2.3 Defining Made-to-order

Most operations management textbooks show the traditional product process matrix and discuss the volume, variety, and flow tradeoffs inherent in process choice. In addition, most textbooks divide manufactured goods into categories such as made-to-stock, assembled-to-order, and made-to-order Historically, these two classification systems were in sync; made-to-order products were best manufactured as projects and job shop processes, while batch and line processes produced made-to-stock items. But in more recent years, these classifications no longer map directly to specific processes. Made-to-order products are available on all process types (Schroeder, 2007, p. 61, Table 4.3) negating some of the distinction found in the product process matrix. In the matrix, only job shop processes produce made-to-order products.

These classifications were further obscured when one considered “custom” orders of significant volume that could be built in repetition perhaps even on dedicated lines. The printing industry is often cited as a made-to-order product since the typeset changes for each job. However, each job could be very high in volume. Therefore, it is not the traditional made-to-order product produced in a job shop, nor a traditional production line product.

In addition, these models and classifications do not adequately reflect the practice of mass customization. Although the made-to-order, engineered-to-order, assembled-to-order classification defines “custom” products made by various process types, these definitions do not incorporate the “mass” component of mass customization. An engineered-to-order product could be developed from the ground up or it could be a variant of another product. Neither of these examples implies mass customization. These distinctions encompass the “customized” part of mass customization, but do not delineate the concept of “mass.”

The made-to-order, engineered-to-order, assembled-to-order descriptions capture the customer involvement portion of mass customization. However, the current matrix or product descriptions do not capture the “mass” or modularity component of mass customization capabilities. Duray *et al.* (2000) look at both customer involvement and modularity of product design to define mass customization types. Each type of mass customizers uses a different manufacturing system or process type. With the spectrum of made-to-order and the different process types for mass customizers, we surmise that in practice, some form of customization is available on all process types. If “one of a kind” is available on all process types then the product process matrix cannot adequately capture this type of customization.

2.2.4 The Paradox of Mass Customization

Mass customization presents a paradox of providing customized goods at low cost. In concept, the basis for mass customization is the ability to provide meaningful customer specifications or variety, and low cost through high volume-related economies simultaneously. The apparent process choice paradox presented by mass customization stems from the conflicting capabilities required. The process choice continuum from one-of-a-kind project based processes through mass produced and continuous processes presented by Hayes and Wheelwright (1979) is no longer adequate to explain the new manufacturing initiatives implied by mass customization. Traditionally, the manufacturing capabilities of low cost could only be achieved with standard products represented by line or continuous processes. Traditional customization is supported through a project or jobbing process where general purpose machines are used to support small lots of unique product. A flexible manufacturing capability to produce custom products could only be achieved at higher fixed cost than standard production using project or job shop methods. Batch systems provided some flexibility over the more standardized processes and lower cost than the more flexible process types. However, traditional definitions of batch systems did not contemplate the ability to provide end user customized products. Mass customization attempts to provide customization using low-cost mass production methods. Therefore, mass customizers are resolving the capability trade-off of cost *versus* customization.

2.3 Defining Mass Customization

Mass customizers resolve the apparent process choice paradox implied by mass customization by constraining the type and degree of customization and the point at which the customer participates in the design process. The earlier the customer enters the design process, the more customized the product will be (Mintzberg 1988). This concept holds true for all customized products. For mass customization, some part of the end product must be produced in large quantities. In essence, a modular design is used to narrow and rationalize the range of choices offered to the customer, thus allowing large batch or mass production processes to be used for part (modules) of the product. The type of modularity determines how standard modules are combined or altered to provide a product made to the customers (constrained) specification. Duray *et al.* (2000) defined mass customization to have these two dimensions of customer involvement and modularity.

Customization implies that the product is altered in some manner to suit the specific needs of a particular customer. For a product to be customized it must be uniquely produced for the customer and the customer must be involved in the design process. Duray *et al.* (2000) used a modified version of Mintzberg's (1988) typology to define customization as taking three forms: pure, tailored, and standardized. Each form differs in the portion of the value chain involved and the degree of uniqueness of the product. Mintzberg's (1988) definitions show that the form of customization represents different levels of customer involvement in the design and production process. These levels of customer involvement in the value chain can be seen to represent different levels of product uniqueness or degrees of customization. The earlier the customer is involved in the design process the more unique the end item. For example, a customer can build a custom home by purchasing land and asking an architect to design a site specific house. This will provide a high level of customization as the customer is involved in the green field design. Alternatively a customer can go to a housing development and choose from an array of home plans making minor modifications on the specified design. In this case, the customer is involved after the base plans are finalized and only minor changes of fit and finish are incorporated. Therefore, this customer has less choice and a less customized product. This view of customization is consistent with the made-to-order, engineered-to-order, assembled-to-order spectrum used in traditional operations management courses.

To gain economies of scale in production, mass customized products must have some common designs or components. For this reason, mass customization is highly dependent on modularity. Modularity provides for the higher volumes required for mass production of low cost components. Pine (1993) developed the concept of how to achieve modularity using the methodologies of Ulrich and Tung (1991). Duray *et al.* (2000) operationalized these modularity types providing specific definitions to be used to identify different types of mass customizers based on modularity type and point of customer involvement. Using a modular product design limits the options available to customers. For example adiamondisforever.com allows the user to determine the exact size of diamond in a ring using a sliding scale. The diamond is a module that can be "swapped' in the design of the ring. This gives the customer a wide range of options on the diamond. However, only two different designs are available to the consumer: a solitaire or three diamond design. The ring design is constrained from that of a "job shop" jeweler where the options are limited only by your imagination, the properties of the metals and jewels, and the skill of the jeweler.

Mass customization works because it restricts the choices of consumers to prescribed options derived through modularity. When modularity and form of customization are combined, a distinct picture of mass customization emerges. Modularity is used throughout the production process to provide different levels of customization through a mix of standard and custom components. A mass customized product is defined as providing end-user specified customization achieved through the use of modularity of components. The end-user specified customization takes the form of customer involvement on the production process which provides the aspect of customization. The "mass" component of the definition provides the economy of scale through modularity of components.

Duray *et al.* (2000) introduced the concept that all mass customizers do not use the same manufacturing processes. The point of customer involvement and the type of modularity in the product design determine the manufacturing process to be used. The traditional product process may consider the level of customization in both the product structure and process design. However, the concept of modularity is not part of the model.

2.4 Developing the New Model – Volume, Variety, and Variation

The new model builds on the traditional product process matrix but better differentiates the concepts of volume and variety while adding a new dimension of process variation, which estimates the amount of changes required of the process. First, the product life cycle is dissected into two pieces: the volume and the variety of the items. Second, the process lifecycle is represented on the diagonal of the matrix. The model is defined using volume to describe the product lifecycle axis, while variety represents the process lifecycle axis. Finally, the third dimension of variation is introduced. Variation captures the concept of standardization in the process, which manifests itself in terms of modularity.

In the product process matrix, the two axes of product lifecycle and process lifecycle are fairly stagnant. Examples are laced on the diagonal to describe the archetypes, but the process types are predefined on the *Y* axis. Therefore the matrix does not allow for newer process configurations such as manufacturing cells or automated technologies. A model using volume and variety on the axes allows for a broader interpretation of process types. The volume-variety matrix shows process types on the diagonal and not on the *Y* axis and therefore it does not preclude other positions in the matrix.

2.4.1 Volume and Variety

The new model disaggregates the product life cycle into two components: volume and variety, and adds a third dimension of process variation. In the new model, volume is thought of as volume for the entire process; *i.e.*, "how many products are produced on the process?" The product life cycle is explicit in differentiating the life stages based on volume of the product (Figure 2.1). Stages I and II are defined as low volume while phases III and IV are higher and of high volume. The translation from the product life cycle to volume is straightforward. For example, a high speed line with a cycle time of one minute would produce up to 480 items *per* 8-hour shift regardless of the configuration of the end items.

The product life cycle also describes the variety of the products in detail. Stage I has "one of a kind products" or high variety, Stage II has "multiple products", Stage III has "few major products" or medium variety, and Stage IV contains "commodity" or few products. In the new model, variety is on the Y axis and is defined as the number of different products produced on the process. A different product is defined as any deviation from the standard output. This would include even minor changes such as color or personalization.

Using "volume" and "variety" on the axes, the traditional process types are defined on the diagonal. Each process type can be distinguished by its volume and variety of products. Projects produce an infinite amount of truly unique products with each individual project completing one or a small number of products. Job shops produce a high variety of products in small volume. Batch processes produce small to medium sized lots of a more limited or preset number of items. Some batch processes have jumbled flows while others have linear flow patterns. Batch processes that have jumbled flows will generally have higher variety than those with linear flows. Line processes produce standardized products with high volumes while continuous processes produce a homogenous flow of non-discrete products. These are the traditional parameters of manufacturing process and they fit the volume-variety matrix.

The volume and variety matrix allows for the possibility of off-diagonal processes. Any combination of variety and volume can be captured on the matrix. The biggest problem is that the current product process matrix and volume-variety approaches do not capture the differences in processes at each predefined step. Using production lines as an example, there are assembly lines that produce products with no variety making the exact same product in massive quantities. This "line" process can be captured on the diagonal. However, the Toyota Production System can incorporate numerous design variants on an assembly line, resulting in a high variety of end items. Toyota's assembly line would occupy the top right corner of the matrix. With this placement, Toyota appears to have an entirely different process type than the traditional auto assembly line. However, the Toyota production process is extremely standardized with one automobile completed approximately every minute. In many practical process terms, the layout of the Toyota assembly line is no different from other automobile producers; it is a linear, automated process with a paced line speed. This radical difference in placement in the volume-variety model does not capture the original spirit of a "process life cycle." The volume-variety model opens up the possibility of producing high variety on automated processes such as a line. However, the placement of the mixed model assembly approach (such as Toyota's assembly line) on the volume and variety matrix does not capture the similarity to the traditional line and over-emphasizes the differences. The differences are more than negligible but not as extreme as the placement on the volume-variety matrix.

The mixed model assembly line requires different operational tasks than a traditional commodity line. First, the mixed model product design process is more complex as multiple models must share the assembly line sequence, timing, and tasks. Second, with multiple models, the correct materials and assemblies must be matched to the correct vehicle at the precise time it arrives at each work station. This requires a refined materials management system. Third, each order must be tracked separately from order receipt until final delivery and each order is assigned to a specific end item. In commodities, there is only one design. All components and end items are identical, thereby simplifying the management tasks and reducing the costs.

Some forms of mass customization appear similar to the mixed model assembly line. The main difference is that mass customization requires that each order be tied directly to an end user customer. Often, mixed model assembly line products are made-to-stock or pulled from distribution, but not by customers, as evidenced by the large finished goods inventory of car manufacturers in the recent economic downturn. The volume-variety model still does not adequately capture mixed model assembly nor most forms of mass customization.

2.4.2 The Third Dimension – Variation

The third dimension process variation is defined as the amount of change required of the process to produce each of the orders (Figure 2.2). This dimension is of particular concern to mass customizers as it reflects the amount of modularity inherent in the product structure. Variation can be represented by the mix of end products that is achieved without stopping the process. For mass customization, this could be restated as the amount of modularity that is in a product design. A more modular product will be able to achieve variation with little interruption.

Following Duray *et al.* (2000), modularity can be employed at different points in the manufacturing cycle: design, fabrication, assembly, and/or use. The point of the manufacturing cycle where modularity is employed will determine the amount of variation in the process. For example, a mixed models assembly line is not stopped to retool for each item but rather flows without interruption. Modularity is designed into the assembly stages of the manufacturing process, and the process is fairly standardized. For mass customized clothing, fabric is cut to specific dimensions in the fabrication stages of the cycle. This requires specific patterns for each customer. However, computer control cutting equipment can retool for this process without delay once the specific dimensions are programmed. For modularity in the design phase, products will require more flexible processes to adapt to the unique requirements. In general, modularity in the earlier stages of the manufacturing cycle will require flexible processes while modularity in the later stages will be less disruptive to the process flow.

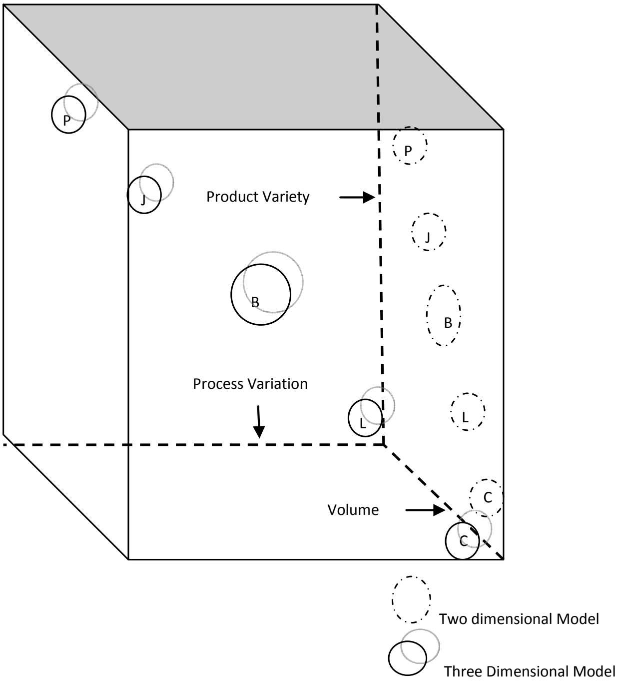

Figure 2.2 Process type placement on the proposed model (project, jobbing, batch, line, continuous)

The classic example of assembled-to-order may have high end item variety but little or no process variation. The Toyota example is easily incorporated into the new model. Toyota has very standardized processes but can produce different variants of their cars through choices of options. Simple color choice or personalization is a very visible differentiator for the customer, while it may have little effect on the processes.

For engineered-to-order products, there may be a much greater distinction in the variation of the process depending on whether modularity is used. In engineered-to-order products without modularity, there will be a great deal of variation in the process as each item is specifically design in its entirety. For engineered-to-order products with modular components, the design and manufacturing lead-times will be much shorter. Some modules will be shared across all products thereby decreasing manufacturing time and cost. The new three dimensional matrix is capable of incorporating both regular and mass customized products.

By looking at each process type, you can easily see how variability occurs in the traditionally defined process types. Each type can incorporate variation. It is through process variation that a distinction can be made within each process type. The three dimensional matrix supports the traditional process types on the diagonal in the cube. Each process type is elongated on the third dimension of variation to show the differences in process variation. For each process, the example archetype now incorporates process variation. Traditional projects have high variety and low volume, but the new model can incorporate either truly unique projects or those projects that have some degree of repeatability. For example, software development projects may present revolutionary new codes and methods and be truly unique endeavors. In opposition, software development projects may as well have a repeatable sequence of steps that are used, and perhaps documented and required to be used, for each new project. With repeatable steps, the process has less variation than if it were a one-time only project. Both of these software development projects can be shown in the new model in the elongated description of the process type.

Job shop processes can have multiple levels of variation. In a traditional job shop, such as a commercial printer, each job would be truly unique. However, if component sharing modularity exists, the core technology or modules of the product are not uniquely designed for each order, resulting in reduced variation in the process. Sharing core technology can be seen in elevator or conveyor systems. The basic technology to create movement is the same in each product. However each unique product is designed to adapt to its specific installation.

Batch processes can contain the highest degree of variation through modularity. Since batch processes operate close to job shops on one side of the continuum and to line processes on the other, they are defined broadly. Batch processes can incorporate many forms of modularity. The type of batch process will be most dependent on the earliest point in the manufacturing cycle where the modularity is employed. If modularity occurs in the design or fabrication stages, the process will most likely have a more jumbled flow. If modularity is designed in the product at the fabrication or assembly stage, the process will have a more linear flow. The placement in the batch category may also be highly dependent on the volume and product variety.

Line processes have been discussed in previous sections. The examples of mixed model assembly lines and traditional standard product lines both occupy a similar space in this model reflecting their similarity in process, regardless of end item variety.

Using the new three dimensional model, one can go back to the original intent of the product process matrix and the ability to see industry, company or process evolution. Individual products can be mapped in the cube (Figure 2.3). Dell is the best known example of mass customization using an assembled-to-order process. The assembly line of Dell is tailored to produce high volume product with variation limited by the module design, with little variation in the process between items. For an engineered-to-order example, escalators are produced for indoor or outdoor use in varying lengths and gradations. However, the basic design of an escalator does not vary between sites. The production process will have some variation but the process steps will be similar for each product. Escalators have higher end item variety as each implementation is different. The product will have lower volumes and the process will have more variation than the Dell example. Modular office furniture is often an example of mass customization which incorporates modularity late in the manufacturing process. For made-to-stock, modular office furniture has great variety as customers can configure their product after

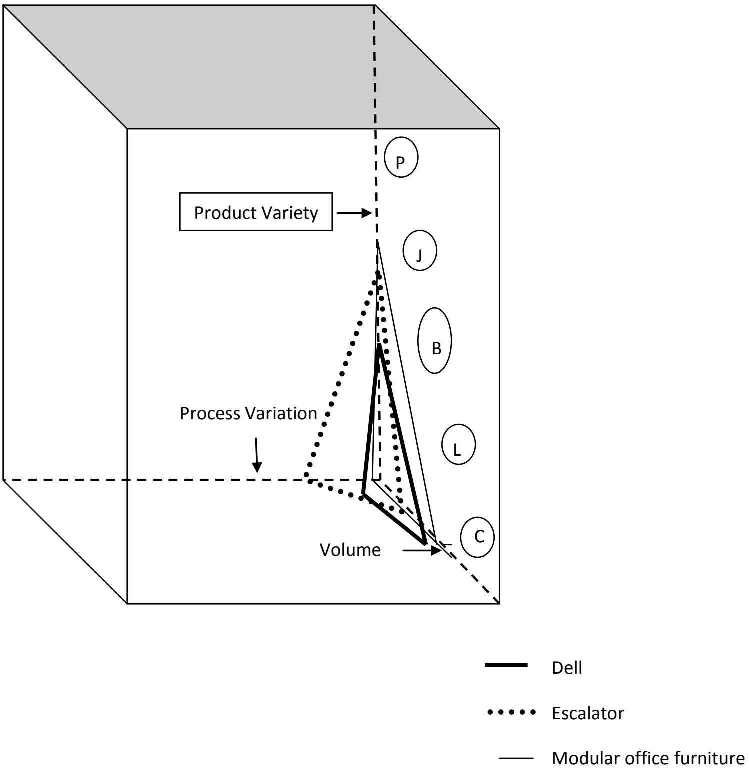

Figure 2.3 Placement of mass customizers on the proposed model

purchase. Since this is a consumer product, volume may be high. The modularity occurs so late in the process, perhaps even in use post sale, that there is little variation in the process. These examples give a small insight into how the new model may be used to map processes.

2.5 Future Directions

One question that immediately arises out of the new volume-variety-variation model is: "Where is the most profitable position on the cube?" For mass customizers, one would assume that the ultimate position on the cube would be high variety, high volume, and low variation. This positioning would portray the ultimate in mass customization capability. However, this position may not necessarily be financially profitable. A market must exist for the product and the functional strategies (marketing, operations, engineering, human resources, information systems, financial aspects, *etc.*) and must be aligned to take advantage of the mass customization capability. The concept of equifinality applies to this model; all positions on the matrix are capable of producing positive performance.

However, the new model can be tested using multiple companies to determine the appropriate environment for each process type. There may be environments where one process type would be more appropriate than another, and which therefore provide a higher financial performance. By examining high and low performers in each section of the cube, key success factors may be determined for each process type. The model could be populated with a large number of example processes to determine all the currently feasible positions. Differences between and within groupings would give a richer look into the components of the operating systems supporting these process types. Industries could be modeled by placing competitors on the cube and determining the relative strategic position of the companies. The new model lends itself to both case study and survey research.

2.6 Conclusion

The volume-variety-variation model provides a fresh perspective on process types in manufacturing. The new model easily incorporates both standard process types and the new competitive capabilities of mass customization. The model deconstructs the product process matrix resulting in a framework that is more adaptable to new process types. The discussion in this chapter introduces these new concepts to be used to better understand the placement of mass customization in the operations management lexicon.

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Chapter 3
Service Customization Through Dramaturgy

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Abstract The customization of a service often depends on the "performance" delivered by front-stage service employees. Drawing on theories of dramaturgy and service marketing, we present a typology of four distinct and viable configurations for achieving different types of service customization. We explain how variations in the time pressure to customize a service, and the degree of customization required, combine to determine the characteristics of each configuration. With service organizations increasingly operating on a global basis, we discuss the

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fit between the preferences of different multicultural segments, the operational characteristics of a configuration, and the level of customization offered.

Abbreviations

FSA	Financial Services Authority
UK	United Kingdom

3.1 Introduction

Mass customization has been one of the most studied and discussed topics of the last 10 years, in the area of operations management, and yet there has been very little research, conceptual or empirical, that examines how service organizations deliver effective forms of customization. This is the case despite the fact that operations management scholars have argued that there is a need for research on mass customization in service organizations (Da Silveira *et al.* 2001, Roth and Menor 2003), and that many service organizations would benefit from “segment of one” strategies (Peppers and Rogers 1999) for “molecular markets” (Day and Montgomery 1999).

With this chapter we seek to address this gap, by presenting a typology that reveals how service organizations might design and manage their processes based on different dramaturgy concepts (Clark and Mangham 2004, Gardner 1992, Goffman 1959, Grove and Fisk 1983, 1997, Grove *et al.* 2000, 2004, Haahti 2003, Ritti and Silver 1986). In particular, we focus on how the “drama” of the service encounters – the engagement of service employees and customers – can be designed to achieve different forms of customization. We suggest that these encounters can be viewed as some form of *adaptive performance* that is acted out by service employees (the actors) for customers (the audience). Using two key dramaturgy concepts, *scripts* (the set of rules and instructions that govern the content and delivery of a service process) and *improvisation* (the ability to rewrite and deliver a script), we explore the range of service customization that can be achieved.

To show how the nature of a service performance can be effectively designed to satisfy different customer expectations, we use two operations management dimensions: the relative time pressure to customize and the degree of customization required. Different combinations of these dimensions result in a typology of four service customization configurations (*embellished customization*, *predetermined customization*, *prompt customization*, and *intuitive customization*), each of which specifies an “operational type” that is defined by a set distinct operational characteristics (Bozarth and McDermott 1998, McCarthy 1995, 2004a).

The characteristics of the service customization configurations that we propose reveal how organizations can use dramaturgy concepts to provide a personalized service in terms of a change in content only, or a change in delivery only, or a change in both content and delivery. By content we mean the core service offering (*e.g*., a meal at a restaurant or a legal document drawn up by a lawyer) and by delivery we mean the interpersonal behavior that service employees use to deliver the core content of the service (*e.g*., variations in attentiveness, tone of voice, and gestures). With variations in these service characteristics we follow the contingency theory view of organizations (Hofer 1975) and argue that service organizations with customization configurations that fit specific and desired customization demands will achieve superior performance over those organizations with customization configuration misfits.

With this focus and using this approach, we make two core contributions: the use of dramaturgy concepts for studying customization and the creation of a typology for understanding how performances can be designed to deliver customized services. Together these contributions respond to the research gap indentified by Johnston (1999, p. 117), who explained that "the service encounter is the crux of service delivery, yet how much do we know about which are the right scripts, attitudes, behaviors to achieve the desired effect?" These contributions, we believe, point to at least three major implications for researchers and managers. First, service organizations should concentrate on one customization configuration only to ensure high levels of configuration fit, otherwise they risk developing a mix of ineffective service customization capabilities. Second, while the effectiveness of the configuration depends on the nature of the service and the context of its operations, the two configurations at the extremes of our typology (embellished customization and intuitive customization), will tend to outperform the other two middle configurations (predetermined customization and prompt customization). Third, and in line with the theme for this section of the book – *Mass Customization and the Global Firm* – the nature of any customization by service performance should be designed to suit different nationalities or cultural segments.

3.2 Background

In this section of our chapter we highlight that there is limited operations management research on service customization and explain why service organizations can benefit from mass customization. From this review of the few studies that have examined the mass customization of services, we identify and justify two customization dimensions – the time pressure to customize the service performance and the degree of performance customization required – that bound and shape our typology. We then present the dramaturgy concepts that we use to explore the range of customization in a service customization configuration, and the associated capabilities.

3.2.1 Customization of Service Operations

While many researchers have debated and studied how industrial companies use mass customization principles to design, build and supply physical products (*e.g.*, Da Silveira *et al.* 2001; Duray 2002; Fogliatto *et al.* 2003; McCarthy 2004b, Salvador *et al.* 2004, Tu *et al.* 2001), there has been a dearth of research on how mass customization applies to the service industry. It is widely recognized that services differ from manufactured products in terms of intangibility (objects *versus* performances), heterogeneity (significant variations in how a service can be delivered and variation in types of customers and their requirements), and simultaneity (the production and consumption of services often occur at the same time) (see Kellogg and Nie 1995). There is perhaps less awareness of the fact that service organizations, relative to manufacturing organizations, have a greater ability and tendency to offer some form of customization. This is especially the case for services with high levels of customer-service employee engagement, as these encounters can be designed and managed to personalize both the content and delivery of the service (Czepiel *et al.* 1985, Lovelock 1984, Schlesinger and Heskett 1992). Pine and Gilmore (1999) have taken this idea further to suggest that what some industries offer, and indeed what consumers want from them, are not services, but experiences that are as distinct from services as services are from goods. The experience economy, they suggest, offers consumers a customized, transformative encounter.

Yet, despite this capacity for service organizations to customize, we know very little about the different "operational types" or "configurations" (Bozarth and McDermott 1998, McCarthy 1995) that underlie the design and diversity of different service customization offerings. Such knowledge is essential for pursuing the three main goals of operations management research: describing, explaining, and predicting the effects of different operational practices (McCarthy *et al.* 2000). Also, while services marketing research has shown that customers from different cultures and nationalities have different expectations about the content and delivery of a service (*e.g.*, Clark 1990, Donthu and Yoo 1998), there has been very little research, with the exception of that by Pullman *et al.* (2001), on what these differences mean when it comes to customizing service operations. Instead, prior research has focused on examining the information technology enablers for modeling, configuring and delivering different customized services (*e.g.*, Akkermans *et al.* 2004, Ansari and Mela 2003, Jiao *et al.* 2003, Meyer and DeTore 2001, Peters and Saidin 2000, Varki and Rust 1998), or has examined the challenges and benefits of trying to implement mass customization concepts in specific service sectors such as catering (Chen and Hao 2007), secondary schools (Waslander 2007), financial services (Winter 2002), and care of the elderly (Essen 2008).

Although the research on technology enablers is important for developing customization strategies for service operations, there are many types of services that are technology-light, relying instead on forms of interpersonal intervention and interaction to provide a personalized service (Bettencourt and Gwinner 1996). These interpersonal encounters typically occur in industries such as banking, management consultancy, healthcare, and hospitality, where the service can be produced and consumed in the same physical location. They offer significant opportunities for designing processes that prompt or constrain different modes of "employee adaptiveness" (Thompson 1989) for creating and delivering effective customization.

We suggest that service organizations can move towards different types of mass customization through an analysis of the operational dimensions that prompt or facilitate different types of service customization. In response, we propose a typology, explained below, which uses concepts from dramaturgy and service marketing.

3.2.2 Typology Dimensions: Time Pressure to Customize and Level of Customization Required

Service customization is dependent both on the potential level of customization the service organization can offer and on the ability of the organization to realistically deliver the required customization within a specific time given the resources and constraints that the company faces. These two requirements correspond to Slack's (1983, 2005) dimensions of manufacturing flexibility: "the range of states a production system can adopt" (2005, p. 1194) and the response, "the ease with which it moves from one state to another" (2005, p. 1194), both of which underlie the two operational dimensions of our typology.

The first dimension of our typology is the *time pressure* to customize, which relates to Slack's (2005) flexibility response in manufacturing and to the notion that the ability to customize is affected by a firm's ability to implement time-based manufacturing processes (Tu *et al.* 2001). We use the term "time pressure" as studies argue that this is the main factor that differentiates unplanned improvised behaviors from planned routine behaviors (Crossan *et al.* 2005), which significantly differentiate the "performance" of service encounters. Time, in particular the speed of service, has also been identified as a determinant of service quality (see Johnston 1999). As we focus on services that involve high levels of employee–customer interaction, the time lag between the requests and the subsequent responses can vary significantly. Consequently, we suggest that these lag variations create different time pressures to deliver a customized service that influences the type of customization configuration required. If the time pressure is low, then service employees have a relative abundance of time to adapt their behavior and the content and delivery of the service. They have the time to determine, plan, and react to any customization requests in a manner that is relatively controlled, detailed and considered. If the time pressure to customize is high, then service employees will rely on intuition and spontaneity, to sense and deliver customization in a real-time and highly simultaneous fashion. In sum, this customization dimension reflects the amount of time a service employee has to scan for and interpret the cues that signal a specific customer need *and* to then customize the delivery and content of the required service.

The second dimension of our typology, the level of customization, relates to Slack's (2005) flexibility range and has been an enduring theme in studies of mass customization in manufacturing (for a review, see Da Silveira *et al.* 2001). However, this prior research is unable to capture the degree of service customization as delivered by front-stage service employees, because it focuses on how the level of customization varies in terms of the manufacturing strategies followed, on the position in the value chain at which the customization occurs and on how and who adapts the products. Consequently, we draw upon the product and process innovation literatures (Dewar and Dutton 1986, McDermott and O'Connor 2002) and put forward simple and fitting categories for the magnitude of customization, in terms of both the content of the service and its delivery. We suggest that a low level of service customization (either in terms of content, delivery, or both) will involve employees incrementally adapting and using existing knowledge and resources (personal and organizational) to adjust a standard service. A high level of service customization, on the other hand, will require employees to access or develop new knowledge and resources, so as to radically alter a standard service either in terms of content, delivery or both.

3.2.3 Dramaturgy

The basic premise of the dramaturgical perspective is that people behave and express themselves according to the situations they face, *i.e.*, they put on an act. Goffman (1959) argued that this was a universal social trait, for as individuals we are torn between the desire to act spontaneously and the need to follow social expectations. He contends that we are conditioned to "put on" acts or performances. In these performances individuals endeavor to persuade others that they are indeed consistent and stable people who play their social roles well.

The dramaturgical perspective has gained much attention in the management literature in general (Gardner 1992, Ritti and Silver 1986, Pine and Gilmore 1998, 1999, Clark and Mangham 2004, Haahti 2003) and in the services marketing literature in particular (Grove and Fisk 1997, Grove *et al.* 2000, 2004). Both researchers and practitioners alike are interested in the fact that employees in service settings function in a very real sense as performers in a drama, and that many dimensions of the interaction can impact both the level of service that customers receive and the satisfaction they express. Hochschild (1983), for example, suggested the term "emotional labor" to describe how employees in a service setting perform when they are required to "feel", or at least to project the appearance of feeling and emotions as they engage in job related interactions. So, for example, employees in a service setting may feel sympathy for a customer's dissatisfaction and are indeed expected by the customer to display that they feel sympathy. As such interactions are central to many service organizations, management researchers have argued that all services are essentially a *performance*, which cannot be held or stored – only experienced (Grove and Fisk 1997, Pine and Gilmore 1998, 1999, Grove *et al.* 2000, 2004). Indeed, Pine and Gilmore (1998, 1999) talk about the provision of experiences that go beyond mere services, they are personalized, transformative events that are deliberately staged, like any theatrical event.

We suggest that the metaphor of understanding services as *theater* is particularly useful for understanding and achieving service customization. It offers a novel approach that service organizations can use to control and manipulate the interaction of the customer with the point of service delivery. The specific drama or theatrical reality of a service operation can play an important role in creating and sustaining value in these types of service organizations, because "*how* the service is performed, *e.g.*, the courtesy and care that is displayed, is just as important as *what* is performed, *e.g.*, the specific tasks that are completed" (Grove *et al.* 2000, p. 21). We suggest that dramaturgy concepts can be used to study how service organizations control and benefit from two critical aspects of employee adaptiveness: the ability to adapt interpersonal behavior and the ability to adapt the core service offering (Bettencourt and Gwinner 1996, Gwinner *et al.* 2005). Also, as Gwinner *et al.* (2005) explain, prior studies on employee adaptiveness have tended to examine only one of these capabilities at a time, despite the fact that some services can be produced and consumed simultaneously. They also reveal that existing research has tended to view employee adaptiveness as a discretionary or "extra-role behavior" that is not formally mandated by service organizations in terms of how they design their processes, and control and reward employees. In contrast, we take the view put forward by Gwinner *et al.* (2005) that adaptive employee behaviors represent a capability that should be formally considered when designing and managing service processes for customization.

To examine how service organizations might use different forms of employee adaptiveness we focus on one of the three "Ps" of dramaturgy (Grove *et al.* 2000) – the *performance* and the types of scripts and improvisation capabilities required to deliver service customization configurations. The other two "Ps" – *participants* and *physical setting* – provide the basis for further research on how these elements can also be used to provide customized services. The participants are both the actors (the service employees) and the audience (the service customers); together they constitute how a service is delivered and received. The service customers may have varied expectations and needs, which they bring to the interaction. Often they must be physically present during the service delivery, just like a theatrical audience, regardless of how humdrum or spectacular the service encounter may be. Furthermore, in some situations, consumers may play a greater role than that of being a passive audience, they become a "*partial employee* of the service organization through co-production or even self-service" (Chase and Erikson 1987, p. 195).

The setting for dramaturgy is the performance interface, and this takes different forms for different services. It may be a physical venue such as a hotel or a restaurant, but equally nowadays it may be a website or a telephone conversation. In terms of service operations management, the interface involves decisions about controlling the flow of information, materials and customers, but in terms of dramaturgy, it also involves what has been called *atmospherics* (Kotler, 1973), which are the features of the interface that produce emotional, physical, and in turn behavioral effects in customers. The interface then in itself serves the function of complementing the performance and setting the scene. As services are highly intangible, these experiences provide customers with extrinsic cues for judging the quality of a service (Zeithaml *et al.* 1988). Consequently, the performance interface offers a *servicescape,* a physical venue, or technological medium in which "the service is assembled and in which the service provider and customer interact, combined with tangible commodities that facilitate performance or communication of the service" (Booms and Bitner 1981, p. 36).

3.2.4 The Service Performance: Scripts and Improvisation

The performance elements of dramaturgy are the process and outcome of the service and its consumption. They combine the actions of both the customers and the service employees, with the effects of the physical setting. The performances given by service organizations are largely delivered to customers by front-stage employees with different levels of expertise and training (*e.g.*, lawyers, doctors, accountants, management consultants, receptionists, and restaurant servers), who engage with the customers. The performance is supported by a range of back-stage staff and systems, which are hidden from the customers. Consequently, for many types of service organizations "the primary determinant of successful customization is the ability and motivation of the frontline customer contact employees to appropriately implement customization strategies in real time" (Gwinner *et al.* 2005, p. 132).

We now turn to describe how personalized performances can vary in terms of how they are designed and controlled through the use of different types of scripts (simple *versus* complex, and fixed *versus* adaptable) and the use of service employees with capabilities that range from fully adhering to the script (*limited improvisation*), to adapting both the content and delivery of the script (*pure improvisation*) (see Table 3.1).

In terms of service operations, a script is a set of formal and informal instructions that specify or guide the actions of service employees. It is essentially the story of how the service experience will start, take place and end. Like service blueprinting or process mapping (Shostack 1984), scripts define the steps and actions in the process, when and where they happen, how they are delivered, the participants involved, what is said, how it is said, and the various props (service tools) to be used. While it is recognized that organizational scripts vary from strong to weak (Gioia and Poole 1984) depending on how precisely they seek to control and direct the steps and actions of a process, our dimensions of time pressure to customize and level of customization required combine to create conditions requiring scripts that vary in terms of how *simple* or *complex* they are, and how *fixed* or *adaptable* they are.

Table 3.1 Service customization through dramaturgy

Dramaturgy concepts	Definition and examples	Customization implications
Performance	A performance is the process and outcome associated with the delivery and consumption of a service. It combines the actions of both the customers (audience) and the service employees (actors). For example, management consultants "put on a show" when trying to convince clients to buy their services	The nature of the performance can vary in terms of the level of what gets customized (the service delivery and/or the service content) and the time pressure to customize it
Scripts	Scripts define the steps and actions in the performance. They specify when and where they happen, how they are delivered, the participants involved, what is said, how it is said, and the various props (service tools) to be used. For example, servers working in a restaurant may have to wear a uniform and speak to customers in a very specific way	The nature of a customized service depends on how complex or simple the script is, or how fixed or adaptable it is
Improvisation	Improvisation is when a service employee rewrites and adaptively delivers a script for a service performance. For example, physicians alter their tone and style (customizing script delivery) and/or alter the service offering (customizing the content of the script) for different patients with different needs	The nature of a customized service depends on the type of improvisation capability, which ranges from limited improvisation (or highly compliant) to pure improvisation

If a script is simple, it consists of a small number of rules and instructions that focus largely on outcomes, rather than specifying in minute detail the way to achieve the outcomes. Complex scripts, on the other hand, consist of a large number of detailed rules and instructions that focus on defining all aspects of the how, the when, the who, and the what, for all of the service process activities. If a script is highly fixed, then the service organization strictly prohibits any deviation from the script. The service performance, both in terms of content and delivery, regardless of whether it is specified in a simple or complex way, must be closely adhered to. However, it is possible for scripts to be partly fixed, so that only the service content is fixed or only the service delivery is fixed, but not both. For example, when patients visit a laboratory testing service for blood tests and other specialized clinical tests, each service employee they engage with, from the receptionist to the phlebotomist, will follow a relatively complex and fixed script concerning the clinical steps involved in taking, labeling, and transporting the blood sample.

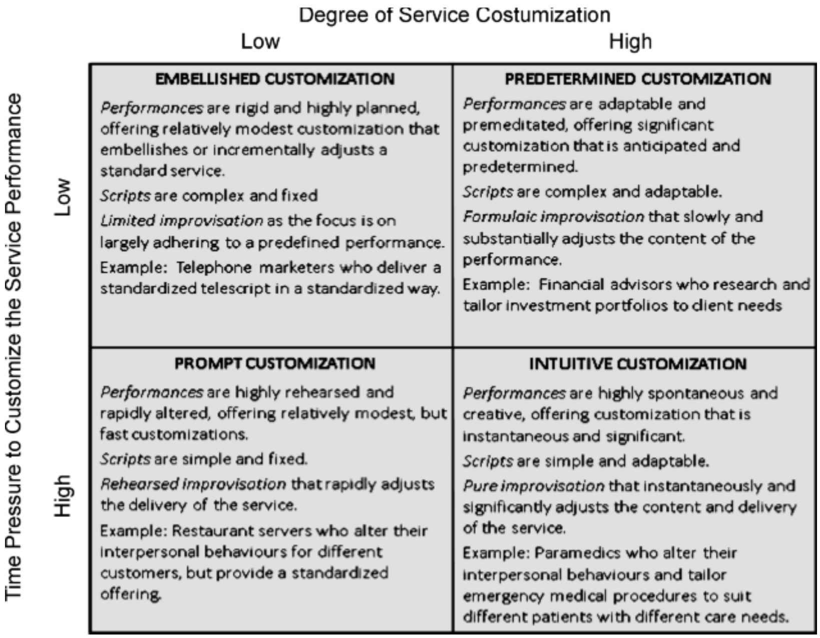
However, the interpersonal communication elements of the service delivery (*e.g.*, tone of voice, vocabulary, and gestures) may vary to suit the age, gender, and ethnicity of the patient. Conversely, if a script is highly adaptive, then employees with appropriate training and expertise are allowed to reactively and proactively adapt the service content and its delivery to suit the needs and expectations of the customer. They may be responding to customized needs that are predicted or unanticipated, and they may be trying to control and manipulate the customer to help ensure a successful performance outcome.

Delivering different types of scripts requires service employees to "act" in different ways, ranging from highly *limited improvisation* to *pure improvisation*. Each type of improvisation requires employees with certain service skills, and job specific experience and knowledge. Limited improvisation, for example, involves closely adhering to the predetermined rules, instructions, and standards that govern the delivery of a service. Service employees with limited improvisation capabilities will tend not to be "mavens", *i.e.*, trusted experts who have problem-solving skills to deliver services in novel ways. Instead, employees with limited improvisation capabilities only "do things by the book" and are unwilling or unable to deviate from the script. As the need for more advanced forms of improvisation increases, this requires employees who are both trained and allowed to rewrite and deliver the script for a service process.

A review by Moorman and Miner (1998) found that improvisation had both a content aspect and a temporal aspect, which were present in a range of organizational and social activities that included sports, management processes, fire-fighting, music, education, theater, and healthcare. In terms of service performances, this means that improvisation involves what gets changed in a script (*i.e.*, instructions concerning the service content, the service delivery, or both), and when that change happens. The greater the change in script content and the shorter the time gap between rewriting a script and delivering the new action, the greater the level of improvisational capability. When the content and delivery are simultaneously adapted, in a spontaneous and seamless manner, we call this the level of *pure improvisation*.

3.3 A Typology of Service Customization Configurations

In this section we explain how the time pressure to customize and the level of customization required combine to produce different service customization configurations. To explore these combinations and the resulting configurations, we present a typology, based on a simplified matrix of time against level of customization. The scale for the time pressure to customize is either low (lots of time available relative to the type of customization required), or high (little or no time available relative to the customization required). Similarly the scale for the level of customization is either high (a radical customization involving a significant change in the content and/or delivery of the service) or low (little or no change in



Degree of Service Costumization

Time Pressure to Customize the Service Performance	Low	High
Low	**EMBELLISHED CUSTOMIZATION** *Performances* are rigid and highly planned, offering relatively modest customization that embellishes or incrementally adjusts a standard service. *Scripts* are complex and fixed *Limited improvisation* as the focus is on largely adhering to a predefined performance. Example: Telephone marketers who deliver a standardized telescript in a standardized way.	**PREDETERMINED CUSTOMIZATION** *Performances* are adaptable and premeditated, offering significant customization that is anticipated and predetermined. *Scripts* are complex and adaptable. *Formulaic improvisation* that slowly and substantially adjusts the content of the performance. Example: Financial advisors who research and tailor investment portfolios to client needs
High	**PROMPT CUSTOMIZATION** *Performances* are highly rehearsed and rapidly altered, offering relatively modest, but fast customizations. *Scripts* are simple and fixed. *Rehearsed improvisation* that rapidly adjusts the delivery of the service. Example: Restaurant servers who alter their interpersonal behaviours for different customers, but provide a standardized offering.	**INTUITIVE CUSTOMIZATION** *Performances* are highly spontaneous and creative, offering customization that is instantaneous and significant. *Scripts* are simple and adaptable. *Pure improvisation* that instantaneously and significantly adjusts the content and delivery of the service. Example: Paramedics who alter their interpersonal behaviours and tailor emergency medical procedures to suit different patients with different care needs.

Figure 3.1 Typology of service customization configurations

the content and/or delivery of the service). High–low combinations of these two dimensions give rise to our four ideal configurations (see Figure 3.1).

3.3.1 Embellished Customization

The first customization configuration that we consider occurs when both the time pressure to customize and the level of customization required are low. This creates a configuration that we call *embellished customization*, as it involves a performance that is rigid and highly planned, so as to deliver minor adaptations of a standardized service in an effective and efficient manner. This configuration does not offer any radical customization of the service content or its delivery. It represents the lowest level of customization in our typology. At best, service employees may fine-tune their interpersonal behavior so as to deliver the service more efficiently and meet service targets. For example, consider telephone marketers and other similar call center type support services. These conversation based performances are highly scripted to ensure service repeatability and reliability. What is spoken, how it is spoken, and the call handling time are all highly controlled and even "recorded for training purposes". There is little time pressure to adapt the service, as no significant customization of the service content and service delivery is allowed by the organization or expected by the customer. This configuration, and the call centers that exemplify it, represent a service customization that is so ra-tional and scientific in nature that it has been called the "Taylorisation of white-collar work' (Taylor and Bain 1999, p. 109), after Frederick Taylor and his *Principles of Scientific Management* (Taylor, 1911).

In line with Frederick Taylor's obsession with control, the performance delivered by embellished customization is based on scripts that are highly complex (*i.e.*, lots of rules and instructions) and very fixed in nature (*i.e.*, service employees are not allowed to rewrite the script). The scripts are delivered by highly compliant service employees who are often physically disconnected from or not visible to the customer (*i.e.*, they are backstage). This form of script delivery involves *limited improvisation* with this configuration, as employees (and sometimes the customers as well) are required to adhere to a detailed set of process instructions, rules, and standards. The service employees are selected and trained to deliver a standard "act" that limits the service content, and how it is delivered, to the rules specified in the script. Employees must follow the script to maintain process reliability and efficiency, and will use and be controlled by technologies and systems that help and constrain them to deliver the performance in a predefined way.

3.3.2 Predetermined Customization

The second service customization configuration in our typology occurs when the time pressure to customize is low and the level of customization required is high. We refer to this configuration as *predetermined customization*, because this combination of dimensions operationally suits a performance that involves significant customization of the service content, for anticipated or premeditated needs. For example, consider the service customization delivered by independent financial advisors in the UK. They are regulated by the Financial Services Authority (FSA), an independent non-governmental body that aims to ensure that they are appropriately trained and accredited to conduct their business with customers in a specific way. The advisors closely follow a complex script that is modularly adaptable, so as to suit the needs of different clients with varying financial circumstances. Thus, the delivery of the service is highly controlled and standardized, and the final content of the core service, the financial product options that are offered, will be customized according to the rules and regulations defined by the script.

To deliver this form of service customization requires what we call a *formulaic improvisation* capability, whereby the service provider has a relative wealth of time to adapt and compile the service content to suit the needs of the customer. The customization is formulaic as the change in service content can be predetermined and formulated into a set of service options. For example, once independent financial advisors have collected information about the circumstances and needs of their clients, they typically have a significant amount of time to research and then formulate a set of financial product options that suits those needs and circumstances. Formulaic improvisation occurs because there is the abundance of time to determine needs and then to devise the content of the core service offering (*e.g.*, the financial products), while the complex and controlling nature of the scripts limit any radical customization of the service delivery itself (*e.g.*, how the financial advisor determines the needs of the customer).

3.3.3 Prompt Customization

The third service customization configuration that we propose occurs when the time pressure to customize is high and the level of customization required is low. We refer to this as *prompt customization*, as it involves rapidly customizing interpersonal behavior to adapt a service in a prompt fashion. This form of customization occurs because there is a high level of employee–customer engagement and significant process visibility (*i.e.*, the service delivery employees are largely on the front stage), which together increase the expectation of customers that they be treated as individuals. However, in this configuration, customers typically understand that the content of the core service is relatively standardized. For example, casual dining restaurant chains such as Pizza Hut, Denny's, or the International House of Pancakes, have relatively standardized but modular menus that allow incremental levels of customization for customers who typically want and appreciate this level and type of service content variety. However, as these types of restaurants tend to compete by emphasizing the delivery aspect of their service, the different types of customers that frequent these restaurants share the expectation that they will be greeted, served, and sometimes even entertained by a service performance that suits their needs.

To provide this prompt form of service customization requires employees to quickly and incrementally adapt and use existing and highly familiar knowledge and resources to deliver the personalized service. We call this *rehearsed improvisation* as it involves employees training and practicing how to act out a simple and fixed script. The script is simple in that the number of rules and instructions is relatively small and largely focused on service delivery outcomes, as opposed to detailing how every service activity should be performed. The script is fixed in that these simple, outcome-based rules must be closely adhered to. Thus, training is given to employees to ensure that they have the diversity of repertoires necessary to recognize, adaptively engage with, and deliver a customized service experience to different types of customers.

3.3.4 Intuitive Customization

The final service customization configuration, which we refer to as *intuitive customization,* occurs when the time pressure to customize is high and the degree of service customization required is also high. While service organizations conforming to any of our proposed configurations will engage in some form of experience that creates an emotional connection with customers (Pullman and Gross 2004), this final configuration focuses on using dramaturgy to create highly personalized connections with customers. Intuitive customization goes beyond carefully reformulating the core content of a service, or rapidly providing an incremental adaptation in the interpersonal delivery. It offers a highly enhanced form of service customization that aims to create memorable and positive impressions for customers. This configuration uses dramaturgy to make customers feel as if they have truly "experienced" a customized service, rather than consumed it.

To effectively engage with and learn from customers, service employees for this configuration must be able to perform tasks and manage the service encounter, with high levels of flexibility and effective attendance. This involves using highly adaptive scripts, which afford the service employees the freedom to tailor the content and delivery of a service to specific customer needs. The scripts are also simple in that they consist of a small number of simple rules that largely govern the desired output of service (*e.g.*, employees at Disney resort hotels are simply charged with making dreams come true), as opposed to detailing how every little action and task should be performed during the service. This script simplicity avoids cognitively overloading service employees, helping them to interpret the needs of different customers and situations, and then use their experience and skills to try to exceed their expectations.

To deliver such highly adaptive scripts requires what we call a *pure improvisation* capability. As defined earlier in this paper, improvisation is a capability that allows service employees to rewrite and deliver the script for a service process; it concerns what gets changed in a script and when that change happens. The greater the change in script content and the shorter the time gap between rewriting a script and delivering its content, the purer the improvisational performance. Studies of improvisation in organizations argue that this capability involves "intuition guiding action in a spontaneous way" (Crossan and Sorrenti 1997, p. 156), as well as "a large skill repertoire, the ability to do a quick study, trust in intuitions, and sophistication in cutting losses" (Weick 2001, p. 352). Thus, pure improvisation is not about undertaking pre-planning that tries to anticipate every service need and situation; it is a reactive and instinctive capability that senses the actions and reactions of customers, and then in real time, simultaneously adapts both the content of the service and how it is delivered, so as to satisfy the needs of customers.

Emergency service providers such as paramedics and the pre-hospital medical and trauma care they provide, exemplify this type of configuration. These service providers have the expertise and training to rapidly diagnose, treat, and transport a vast diversity of patient types, with an equally vast diversity of disorders and care needs. Sometimes the situations faced by paramedics, and other similar service professionals such as firefighters are so unusual and unfamiliar that it feels like "*vu jade* – the opposite of *deja vu*: I've never been here before, I have no idea where I am, and I have no idea who can help me" (Weick 1993, pp. 633–634). In such situations the successful customization of the service involves performances whereby the actors (*e.g.*, the emergency professionals) learn and act on the spot, so that the composition and delivery of unique life saving scripts is a seamless and just-in-time act.

3.4 Discussion and Implications

We believe that this chapter offers two core contributions to research on the mass customization of services, which will prompt future empirical research to test the role of scripts and improvisation in customizing the service encounter. First, by introducing and using dramaturgy, we present a novel and appropriate approach for envisaging and studying the two options that service employees have for customizing a service encounter: interpersonal adaptive behavior and service-offering adaptive behavior (Gwinner *et al.* 2005). To do this, we focus on the design of the service encounter (*i.e.*, scripts) and on the training and delivery capabilities (*i.e.*, improvesation) required. These concepts provide a novel and useful approach for facilitating future operations management research on how service performances may be customized to suit the tastes of different customers, both locally and globally.

Our second core contribution is the typology and its descriptive, explanatory, and predictive insights. Existing service typologies use customization combined with the degree of customer contact as one dimension and the degree of process labor intensity as the other dimension (Chase 1981, Schmenner, 1995, 2004). Our typology offers two different customization specific dimensions, the relative time pressure to customize and the degree of customization required to reveal how the speed and magnitude of the desired customization will affect the "performance" of the service encounter. The descriptions of each of the service customization configurations in our typology help to explain how the design and delivery of these encounters can vary for different customization dimensions. As we suggest in the next section when we discuss the implications of this typology, the configuration descriptions also provide a basis for developing and testing specific predictions about which service customization configurations will be successful under a particular set of circumstances and for testing which combination of scripts and improvisation options would be most effective under a particular set of circumstances. In sum, like typologies in general, ours provides a framework for other researchers to test how our proposed configurations and their variations might influence service performance. We now discuss three implications of these contributions that have relevance for both academic research and management practice concerned with the customization of service operations.

3.4.1 Configuration Fit

In line with prior service management research on strategic fit and focus (*e.g.*, Schmenner 1986, 2004, Staughton and Williams 1994), we suggest that those organizations that ensure that their individual processes are focused on one service customization configuration are likely to be more effective than those service organizations that use multiple configurations at the same time or a hybrid of multiple configurations. This we suggest is largely because there are risks and tradeoffs in trying to be configurationally ambidextrous. However, while this notion of focused operations is consistent with Skinner's (1974) seminal work on the issue, most of the work that supports this view is based on firms operating in relatively stable environments (*e.g.*, Stobaugh and Telesio 1983, Hayes and Clark 1985). Consequently, others have argued that in more dynamic environments organizations should be less focused or specialized, as this helps them to quickly shift or adapt their operations in line with changes in their environment (see Mukherjee *et al.* 2000).

Thus, our typology and its configurations provide a theoretical basis for studying strategic fit issues in service customization. Researchers can empirically examine the fit of each configuration, within its external context, through the use of the customization dimensions that we suggest define and support each customization configuration. Researchers can also investigate internal fit by studying the consistency between the types of scripts and improvisation capabilities proposed for each configuration, as well as their consistency with variations in the two other dramaturgy elements: participants and physical setting.

3.4.2 The Lure of the Diagonal

Typologies of service strategies in general (*e.g.*, Schmenner 1986, 2004), product-process strategies (Hayes and Wheelwright 1979), and corporate strategies (*e.g.*, Porter 1980), all suggest that competitive forces compel firms to focus on attaining the extreme configurations available. The perception is that these extreme configurations offer the greatest potential for high performance relative to the other intermediate configuration options available, because they provide the greatest focus on either lowering costs or adding value. In our typology these extreme configurations represent a diagonal between the top-left quadrant (*i.e.*, the no frills customization – *embellishment*) and the bottom-right quadrant (*i.e.*, premium experiential customization – *intuitive*). The lure of this diagonal and its perceived performance returns provide an interesting proposition for empirical validation. One approach for doing this would be to identify service organizations in different industry contexts that conform to each of the configurations, and then to assess customer perceptions of service quality. This approach would acknowledge that even though the potential for greater effectiveness may be on this diagonal, the best configuration will depend on the characteristics of the service industry and its offering and location in the world.

3.4.3 Global Services and Customizing the Performance

Our chapter also has implications for understanding how service organizations should operate globally and address different cultural segments. In particular our focus on the service encounter as a theatrical performance provides a basis for investigating the customization strategies that service managers might implement to address the different preferences for service customization that exist in different countries.

Prior research on service differentiation strategies for global markets can be simply divided into two camps (see Pullman *et al.* 2002). There is the view that global service organizations should not design processes that are significantly adapted for different markets and neither should a global service model seek to significantly customize the content or delivery of the offerings (Heskett 1987). Instead, service organizations should develop internationally strong brands and rely on the appeal and familiarity of the global service to create a force that will eventually overcome any service-cultural preference misfit that might exist. For example, McDonald's have successfully transferred their service operations model around the world, with limited adaptation of its content and delivery (Pullman *et al.* 2001). When this service strategy is both appropriate and possible, we suggest that it will involve service encounters based on our embellished configuration. This configuration offers process design characteristics (*i.e.*, complex and fixed scripts), and process delivery capabilities (*i.e.*, limited improvisation) that are consistent with the aim of largely maintaining a relatively standardized service offering. This approach to customization is so limited that it offers a people-based and service encounter approach to achieving global service operations that complements the "service factory" (Levitt 1972) and "industrialized intimacy" (Kolesar *et al.* 1998) models, both of which have typically relied on using information systems to track a customer's history and preferences for personalizing limited aspects of the service (Pullman *et al.* 2001).

The second major view of service differentiation strategies for global markets is that certain markets have cultural expectations that will require managers to customize and operate services that suit these needs (Mathe and Perras 1994). If such service customization involves significant adaptation of the service content, then this will require the complex and adaptable scripts and formulaic improvisation that define our predetermined customization. If a regional context requires a service to be customized primarily in terms of its delivery, then this would involve the simple and fixed scripts that characterize prompt customization. Moreover, if the expectations are such that both the content and delivery of the service must be radically altered on a regular basis, then this would suit the scripts (simple and adaptable) and the pure improvisation that defines intuitive service customization.

3.5 Conclusion

Although mass customization has captured the attention of academics and business leaders for nearly 25 years, prior operations management research on this topic has tended to overlook how mass customization might function in service organizations. As service organizations represent a growing segment of the overall business sector and are becomingly increasingly globalized, we believe that it is important to identify and examine the operational configurations necessary for delivering different types of service customization. Introducing ideas from dramaturgy and from service marketing, this chapter provides a novel and powerful typology for conceptualizing and studying the diversity and design of customization in service organizations. We believe the dimensions of the typology and the resulting performance configurations and their defining scripts and improvisation capabilities, provide descriptive, explanatory and predictive contributions that will have significant theoretical and practical impact.

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Part II

Engineering and Management of Mass Customized Products

Chapter 4
NPD-SCM Alignment in Mass Customization

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Abstract This chapter aims to develop a new product development supply chain management alignment framework for mass customization. A case study conducted in industry motivates this framework. Variety, modularity, and innovativeness are the product features that should be taken into account when studying alignment in a mass customization setting. From the supply chain viewpoint, configuration, collaboration, and coordination complexities are the variables that matter. We formulate ten propositions explaining the relationships between the variables of the framework. It must be noted that innovativeness, a variable that has so far been neglected with respect to the alignment question, plays a critical role in supply chain management decisions.

Abbreviations

BOM	Bill-of-materials
JIT	Just in time
NPD	New product development
OEM	Original equipment manufacturer
SCM	Supply chain management

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4.1 Introduction

Mass customization is a business strategy that aims to produce and distribute customized goods at costs that are low enough to target a mass market (*e.g.*, Abdelkafi 2008, Da Silveira *et al.* 2001, Pine 1993); it requires a high degree of flexibility in manufacturing (Fogliatto *et al.* 2003) and along the supply chain. The application of mass customization is not a mere adaptation of available processes to a new environment; the strategy imposes radical changes in the way of doing business (Brown and Bessant 2003). Very frequently, variety proliferation is mentioned as the biggest problem challenging the pursuit of mass customization. High variety can induce operational inefficiencies (*e.g.*, Da Silveira 1998), sometimes leading the manufacturing firm to give up the entire customization program.

Researchers investigated the relationship between variety and supply chains (*e.g.*, Fisher 1997, Randall and Ulrich 2001). The study of this relationship is relevant because of two reasons. First, since the variety created at the design phase is manufactured and distributed within the supply chain, it determines a high portion of the costs of operating the supply chain. Second, the magnitude of the operational effects of variety on the supply chain depends on the adequate choice of supply chain practices, *e.g.*, outsourcing, supply chain structure, positioning of the production sites and warehouses (Blackhurst *et al.* 2005), and supply chain strategy (Childerhouse *et al.* 2002). In other words, for a given level of variety, a particular supply chain practice leads to a better operational performance than another.

To satisfy customers' requirements better and to stay competitive, mass customization companies continuously update their product offers. The increased rate of new product introductions calls for adaptations of the supply chain. Therefore, supply chain management (SCM) and new product development (NPD) should be aligned, so that new products can be transported and delivered at the targeted cost, time, and quality. NPD-SCM alignment allows the manufacturing firm to overcome problems such as product unavailability due to insufficient capacities of supply, production, and/or distribution (Van Hoek and Chapman 2007).

So far, however, there is no comprehensive framework that determines the right actions leading to NPD-SCM alignment in mass customization. The strategy requires, *per se*, a very responsive supply chain and the application of specific design rules. Alignment leverages supply chain capability enhances the effectiveness of product introduction and firm performance (Van Hoek and Chapman 2006). Management practice needs a tool that outlines the supply chain areas more impacted by the introduction of new products in mass customization. The tool aims to support the identification of recommendations that enhance supply chain performance. This chapter aims to fill this gap in the literature.

In our analysis, we concentrate on the focal firm, which develops the new product and designs the supply chain. The remainder of this chapter is organized as follows. In the next section, we discuss leading literature on NPD-SCM alignment and mass customization. Section 4.3 discusses the framework, while formulating propositions. The final section concludes and provides directions for future research.

4.2 Literature Background

Mass customization defines the frame of analysis, whereas NPD-SCM alignment represents the main investigation area. Mass customization imposes requirements on NPD and SCM simultaneously.

4.2.1 NPD-SCM Alignment

NPD is the process of transforming a market opportunity and a set of assumptions about product technology into a marketable product (Krishnan and Ulrich 2001, Weelwright and Clark 1992), whereas SCM is the approach to designing, organizing, and executing all the activities along the value chain from planning to distribution, including the network of suppliers, manufacturers and distributors (Childerhouse *et al.* 2002, Vonderembse *et al.* 2006).

SCM and NPD are necessarily related because, at the end, the supply chain produces and delivers end products that are the output of product development. Most NPD-SCM alignment models assume that product design decisions have already been made (Simchi-Levi *et al.* 2002). Recently, an increasing emphasis on the coordination of SCM and NPD has become noticeable (Hult and Swan 2003, Rungtusanatham and Forza 2005). The approaches that tackle this issue are either NPD-oriented or SCM-oriented (Table 4.1).

Table 4.1 NPD and SCM-oriented approaches

NPD-SCM alignment approaches / Criteria	NPD-oriented approach	SCM-oriented approach
Main focus	Product development	Supply chain
Problem statement	Given the supply chain constraints, find an adequate product design	Given the product design, find the best supply chain that optimizes performance
Solution	An optimal BOM or product architecture	The optimal supply chain strategy or supply chain structure

The NPD-oriented approach may be called "design for supply chain management" (Lee and Sasser 1995); it anticipates supply chain constraints at the early stages of product design. Decision support models of the NPD-oriented approach either consider bill-of-materials (BOM) or product architectures. Models using BOM express relevant costs such as transportation and inventory costs as a function of the product structure. Then, the cost function is optimized to find the best BOM for a given supply chain (Blackhurst *et al.* 2005, Huang *et al.* 2005, Lee and Sasser 1995). Product architecture-based models are used more frequently. Product architecture is "the scheme by which the function of the product is allocated to physical components" (Ulrich 1995, p. 420). Krishnan and Ulrich (2001) argue that the trade-offs between product, process, and supply chain design are better addressed by considering product architectures (modular *vs.* integral) than BOM. Many models analyze the relationships between product architecture characteristics and supply chain decisions (Fixson 2005). Some models deal with the selection of the appropriate sourcing strategy (Novak and Eppinger 1998); other models focus on postponement and the placement of the differentiation point in the supply chain (Feitzinger and Lee 1997).

SCM-oriented literature proposes two types of approaches. The first approach defines supply chain strategy (*i.e.*, lean, agile, or hybrid) depending on product and market-related variables such as demand variability, variety level, and demand volumes (Vonderembse *et al.* 2006, Huang *et al.* 2002, Fisher 1997). The second approach analyzes the impacts of various product structures on supply chain design decisions. Very frequently, such approaches consider the modularity level and product variety (*e.g.*, Salvador *et al.* 2002). Further studies focus on the impact of product modularity on supply chains (Fine 1998).

The NPD process determines the variety level to be produced. Variety is a multi-dimensional concept that can be divided into external and internal variety. External variety is seen by the customers, whereas internal variety is related to the diversity of components and semi-final products (Pil and Holweg 2004). In addition, variety has a static and dynamic component. Static variety represents a single snapshot of the variety handled by the manufacturing firm whereas dynamic variety reflects the whole picture as variety evolves. Dynamic variety is the product mix that a company creates over time in order to serve the marketplace better. The optimization of business processes for a given static variety without considering the dynamic impacts of new product introductions may have detrimental effects on operations. There is no reason that a supply chain system that is optimal for a given variety stays optimal when the level of variety changes.

4.2.2 Mass Customization

Mass customization is a hybrid business strategy that focuses on the fulfillment of individual customer requirements at high efficiency. Mass customization has proven to be very successful in many industrial environments; it enables companies to improve profits and outpace competitors. These advantages can be achieved, however, only if manufacturing firms can accommodate the changes imposed by the strategy. It is not by applying mass production principles that products can be customized effectively and efficiently. Mass customization induces many changes on operations, reaching from product design over manufacturing and assembly to marketing and sales. Taking into account the main topic of this paper, we only focus on mass customization implications on product design and supply chains.

The implementation of mass customization calls for the application of adequate design rules that minimize product lifecycle costs. Product design for mass customization should address the conflicting goals of reusability and differentiation (Robertson and Ulrich 1998). In this respect three approaches have been recommended so far: commonality, modularity, and platform strategies.

Component commonality (Collier 1981) means that a few components are used on a large number of products. A high level of end variety does not necessarily trigger a high variety of components. A study in the automotive industry shows that external variety and internal variety are uncorrelated (Pil and Holweg 2004).

The development of products around modular architectures is the best way to achieve mass customization (Pine 1993). Modularity has been defined in many different ways in the academic literature. Ulrich (1995) requests a one-to-one mapping between functional requirements and physical components to refer to products as modular. Although this requirement ensures a high level of modularity, the one-to-one relationship is rather the exception than the rule in the real world. Very frequently, product architectures are located on a continuum, reaching from completely integral to perfectly modular designs. Thus modularity is a matter of degree (*e.g.*, Salvador *et al.* 2002); it denotes a multidimensional rather than a one-dimensional property of products (Abdelkafi 2008).

In a mass customization setting, modularity should enable the creation of a large number of product variants by mixing and matching a small number of building blocks. To achieve this, interfaces must be standardized, in such a way that the building blocks are built into many different products. Interfaces "describe in detail how the modules will interact, including how they will fit together, connect, and communicate" (Baldwin and Clark 1997, p. 86). Interfaces are part of the visible design rules, which are shared among the supply chain partners in order to ensure that the product can function as an integrated whole. The hidden design parameters, however, are related to decisions that are restrained to the local design of product modules (Baldwin and Clark 1997). Modules may also be carried over several product generations. That is, the manufacturing firm updates or generates new products by varying a small number of modules, while keeping a subset of modules unchanged over time. In this way, the economies of substitution are likely to be achieved. These economies arise when the costs of designing a better system through the partial retention of existing components are lower than the costs of designing it afresh (Garud and Kumaraswamy 2003).

The third variety management approach to ensure distinctiveness and reusability is product platforms. A platform has been defined differently in the academic literature. Some authors (*e.g.*, Meyer and Lehnerd 1997) refer to platforms as the whole set of modules to derive product variants; others (Piller and Waringer 1999) consider it as the basic module, which is common to an entire product family. The latter definition imposes strong constraints on the product architecture; it not only requests modularity, but also an extreme level of commonality of one or more core modules.

When dealing with variety, however, firms mostly focus on optimizing the static variety, thereby neglecting its dynamic nature. Especially in mass customization, is variety unlikely to be static. Static variety cannot fulfill customer requirements, as tastes and preferences evolve in the course of time. In effect, today's product program does not satisfy future customers' needs.

Beside product design, mass customization imposes several requirements on the upstream and downstream parts of the supply chain. The upstream part deals with the transportation, consolidation and warehousing of materials and components required in production. The downstream part concentrates on the packaging and shipment of end products to customers.

The upstream supply chain should ensure that components and modules are delivered on time according to the production schedule. The downstream supply chain delivers on a *per* item basis, since customized products are directly shipped to the customer. It also can carry out a part of the customization process if customers can choose among different logistics options of packaging and transport. Customized packaging (*e.g.*, gift wrapping) and individual delivery are two options that show how to involve supply chain logistics in the customization process (*e.g.*, Riemer and Totz 2001). A smooth functioning of the upstream and downstream supply chains is highly relevant because poor delivery reliability may make customers doubtful about the benefits of mass customization.

4.3 Aligning NPD and SCM in Mass Customization

Most variety management approaches preferably concentrate on static than dynamic variety. When variety-related problems emerge in the supply chain, the common reaction of firms is to reduce the number of produced variants by changing production plans. Though this action decreases the extent of variety and improves operational efficiency, it does not tackle the problem at its very origin; it is only a reactive measure with a short term reach. As customers' requirements change rapidly, new products have to be introduced more frequently. If the company does not consider the impacts of this new variety on the supply chain, it is very likely that a firm's operational efficiency deteriorates, thus leading the company to react again by reducing the level of variety in order to cut costs.

The mere reaction to a problem cannot be an effective approach to improve efficiency. A proactive approach that anticipates the effects of changing variety is therefore advantageous, as it avoids costs before they are incurred. In other words, the interdependencies between dynamic variety, introduced at the product design phase and supply chain should be examined already at the early phases of product development. By anticipating the effects of the new variety on the available supply chain, the company may adapt the suppliers' network to accommodate this variety better or may decide to not introduce the new products at all. In both cases, the proactive approach seems more powerful than the reactive approach. In fact, research on proactive approaches to align NPD and SCM is still in its infancy. Based on a review of the literature, however, Ellram *et al.* (2007) conclude that there is substantial theoretical evidence that proactive approaches provide beneficial outcomes to organizations.

Dynamic variety has far-reaching impacts and influences the design and configuration of the network of suppliers and distributors. The degradation of the cost structure results not only from variety but also from NPD-SCM misalignment. Putting it simply, the supply chain incurs high costs if the supply chain cannot accommodate the level of variety offered to the customers. Because variety is likely to be very high in a mass customization environment, the alignment issue gains importance. For a given level of variety, two different supply chains can lead to different cost structures. Previous studies also demonstrate that supply chain management decisions can help to mitigate the negative implications of product variety on operational performance. For instance, researchers (*e.g.*, Randall and Ulrich 2001) found that locating suppliers of high variety components next to the target market of end products can reduce inventory costs.

To check the impact of dynamic variety on the supply chain, we conduct a case study. The firm under analysis is the electronics division of a European multinational company in the medium-to-low-voltage electrical appliances sector. The firm is characterized by a high and growing product variety. Recently, it refreshed its product range by introducing a new line that deeply changed the structure of its offer. To collect data, a case study protocol was generated. Interviews were carried out with the supply chain director and manufacturing plant manager. Documentary and data analysis, *e.g.*, the distribution of sales *per* item, comparison of the workloads on the processes involved in the manufacturing of the old and the new product lines were also performed.

The introduction of the new line has resulted in an increase in the number of end products and technologies to be managed both in products and production processes. The new products contained new electronic components and new process technologies. This led to an increase in the relative importance of purchasing over manufacturing, in inter-site dependency for the main plant producing the final products, and the need to look for new purchasing markets.

Despite all of this, the consequences of the introduction of the new line and the change in nature of the firm's catalog on supply chain structure were not at first fully evaluated. The supply chain structure and systems were not adapted to the new situation. As a result, operational performance declined.

Using selected key metrics, we noticed that the supply chain is not capable of transporting and delivering the product variety that the plant can produce. In particular, the quotient of the count of different manufactured items (MC_i) and the count of different demanded items in the *i*th working week (DC_i) has been computed. This metric is called tracking ratio: $TKR_i = MC_i/DC_i$. The tracking ratio measures supply chain capability of delivering variety compared to the market need for variety. In the firm's context, demand for variety DC_i increased after the introduction of the new line, whereas the weekly manufactured items MC_i were the same as before. Consequently, the supply chain, as designed and managed, was unable to deliver the new variety mix requested by the clients. This gap is due to the misalignment of SCM and product variety originated by the introduction of the new line.

The case study demonstrates the relevance of aligning SCM and product variety in the course of time. A deeper analysis reveals that the roots of the problems are located in a specific aspect of the dynamic variety. Not every modification of the product and in the level of variety must be associated with changes in the supply chain. For instance, if new variety is created by upgrading a module that can be produced and delivered by an old and reliable supplier in the network, the products change, but supply chain does not.

Based on these ideas, we propose to develop a comprehensive NPD-SCM alignment framework for mass customization. As can be seen in the literature review, NPD ascertains four product properties that are relevant to the supply chain: static variety, dynamic variety, modularity, and innovativeness. Academic and practitioner literature has already recognized the relationships between modularity, static variety, and supply chain performances, but it has neglected the impact of product innovativeness and dynamic variety. Our discussion will explain the relationship between dynamic variety and innovativeness and why they should be considered when dealing with NPD-SCM alignment. In the following, the main variables of the NPD-SCM framework and the relationships between them will be discussed.

4.3.1 Innovativeness and Dynamic Variety

Innovativeness is the degree of novelty of an innovation. It can be measured from the viewpoint of an entire industry, a firm (Garcia and Calantone 2002), or the final market (Danneels and Kleinschmidt 2001). Market innovativeness is related to the external variety, which customers can see and perceive. To produce it, the company may need to create internal variety such as new components and/or modules. Though unperceived by customers, internal variety is frequently necessary to enable market innovations. According to Garcia and Calantone (2002), the elements of novelty of an innovation can be looked for in 17 spheres, including technology, product line, process, and product.

Innovations are the output of innovation projects. Different innovation projects come up with different degrees of innovativeness. New concepts are developed within breakthrough projects and lead to completely new products. Architectural innovations involve new platforms or changes in existing product architecture; they are developed within platform projects. Finally, derivative projects give rise to new module or component innovations (Wheelwright and Clark 1992).

When an innovation is introduced, the variety that is managed by the supply chain can change. Dynamic variety accounts for the change in the product mix. Innovativeness measures the magnitude of change introduced by the innovation project in terms of product novelty for the supply chain. In the consumer-electronics industry, we believe that dynamic variety and innovativeness are negatively related, *i.e.*, highly innovative product development projects are associated with low dynamic variety. Because of the combined effects of innovativeness and variety on the supply chain, we do not expect firms to launch highly innovative products in many versions. Firms with high performance offer high variety when the innovativeness degree is low. This hypothesis is very important and should be checked empirically, as it enables one to discover how highly performing supply chains ensure NPD-

SCM alignment. For instance, the "MacBook Air" is an extremely innovative product launched by Apple Inc., however it is sold in two versions only (source: http://store.apple.com). The validation or rejection of this hypothesis needs intensive empirical work and can represent the subject of future work.

4.3.2 Supply Chain Configuration, Collaboration, and Coordination Complexity

SCM studies can be grouped by the decisions they deal with. Supply chain design research (*e.g.*, Delfmann and Klaas-Wissing 2007) focuses on the topological features of the logistics network and the level of collaboration among partners in the supply chain. Supply chain planning and execution literature tackles the decisions regarding the methods and tools to use in a supply chain, once it has been built up, in order to achieve efficiency and service level requirements (Simchi-Levi *et al.* 2002). The application of mass customization strategy requires making decisions on the supply chain topological features and collaboration levels, as well as the planning and execution tools. Supply chain characteristics depend on these decisions. To capture the characteristics of the logistics network, the descriptive model by Hieber (2002) can be used.

According to Hieber (2002, pp. 63), a supply chain can be described by three main dimensions: configuration, collaboration, and coordination. Configuration refers to "the modelling of the existing business relationships between the network entities." Collaboration "describes the degree and kind of partnership between the participants"; it deals with the level of mutual trust and openness between the actors and whether or not the network strategies are aligned. Coordination describes "the daily operations of transcorporate processes and methods in the logistic network", *e.g.*, the intensity of use of IT tools to support activities, and the autonomy in the planning decisions. A list of measurable complexity drivers is associated to each dimension (Hieber 2002, pp. 63).

Hieber (2002) defined a direction of increasing complexity for the drivers that characterize all three dimensions. For example, the use of integrated systems for planning and execution among partners indicates higher coordination complexity, as compared to the mere fulfillment of orders and delivery. Since each supply chain can be described in terms of Hieber's complexity drivers, the complexity of configuration, collaboration, and coordination can be measured. These metrics can summarize the main features of the supply chain.

4.3.3 Supply Chain Performance

Mass customization aims to provide the market with customized products efficiently. NPD-SCM alignment is fundamental for achieving mass customization objectives. To evaluate NPD-SCM alignment, effectiveness and efficiency performance must be monitored. In particular, the delivered mix of products must be compared to customer orders, and the actual costs must be measured to assure that efficiency targets are achieved. In a mass customization setting, these comparisons allow for assessing, on the one hand, whether the level of customization is actually satisfied, and, on the other, whether the firm is facing operational problems such as overstocks.

4.3.4 Alignment Framework and Propositions

NPD-SCM alignment depends on the right choice of supply chain features, given the product characteristics. These choices should aim to achieve mass customization objectives. We develop a NPD-SCM framework that shows the relationships between product and supply chain characteristics. The arrows in the framework designate direct effects of one variable on another but no indirect effects, as these can be deduced logically. For instance, if variable 1 affects variable 2, which in turn has an impact on variable 3, then the indirect effect of 1 on 3 is obvious. In order to avoid redundant information this type of relationship will not be not represented in the framework. An arrow from 1 to 3 should be drawn only if the first variable directly affects the third one in some way (Figure 4.1).

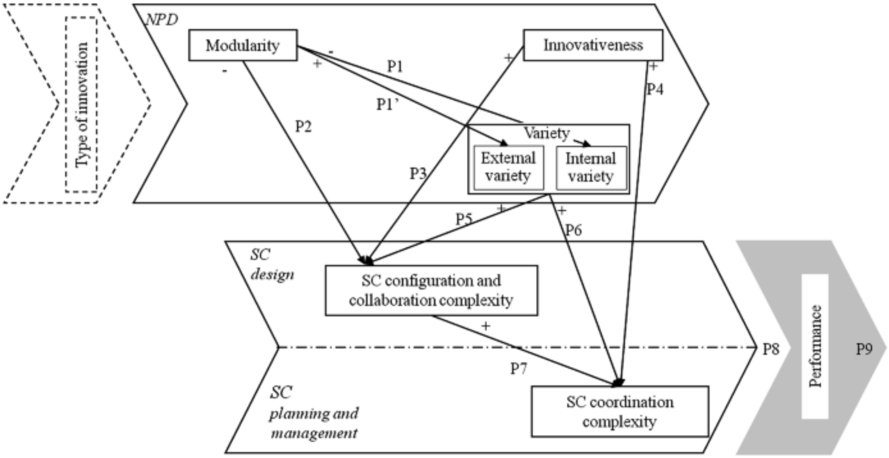

Figure 4.1 The NPD-SCM framework

4.3.4.1 Modularity

Modularity is fundamental in a mass customization setting. It increases external variety because it enables companies to mix and match modules into different end products and reduces costs due to the economies of scale and scope. When a new product with a modular architecture is introduced, the number of end variants (dynamic variety) is likely to increase. Modularity, however, has a negative effect on internal variety. A large number of end variants can be produced by using a few modules (internal variants).

> *Proposition 1a (P1a): Modularity increases the level of external variety offered to the customers.*
>
> *Proposition 1b (P1b): Modularity reduces the level of internal variety handled by the manufacturing firm.*

The module interfaces make it possible for module suppliers to work independently (Fine 1998 Sturgeon 2002). Ro *et al.* (2007) show that in response to product modularization, leading car producers reduced their supplier base. Module suppliers now assemble entire product modules and coordinate large component sourcing networks (Doran *et al.* 2007). From the viewpoint of the firm, which sells the end product under its brand name (*e.g.*, original equipment manufacturer, OEM), the complexity of supply chain configuration is reduced. To assure high quality and reliable delivery, OEMs should develop trust-based buyer–supplier relationships with their module suppliers, while aligning their strategies (Sako and Helper 1998). That reduces collaboration complexity from the OEM's viewpoint. Consequently, we can state the following proposition:

> *Proposition 2 (P2): Modularity reduces the level of configuration and collaboration complexity.*

4.3.4.2 Innovativeness

According to the case study presented above, supply chain decisions are not only based on product modularity; the degree of novelty of the introduced product should also be taken into account. Platform projects, an example for highly innovative projects, call for deep changes in product architectures and may lead firms to work with new suppliers or even to in-source some production activities. In both cases, supply chain complexity increases. The multiple case study research by Caridi *et al.* (2008) shows that highly innovative NPD projects result in a higher increase in supply chain configuration, collaboration, and coordination complexity than less innovative NPD projects. Therefore, we state the following:

> *Proposition 3 (P3): Innovativeness increases supply chain configuration and collaboration complexity.*
>
> *Proposition 4 (P4): Innovativeness increases the level of supply chain coordination complexity.*

Innovativeness measures the magnitude of the novelty from the viewpoint of the firm that introduces the innovation. Therefore, if two firms A and B introduce a new product with the same variety level, but with different degrees of modularity and innovativeness, our framework expects different changes in the features of supply chains A and B. Figure 4.2 depicts the relative magnitude of the changes of supply chain configuration and collaboration in different scenarios, depending on modularity and innovativeness.

Let us look in-depth into studies dealing with the effects of product modularity on supply chains under the light of the framework. At a first glance, contradictory results can be seen. Doran *et al.* (2007) noticed that modularity led to higher collaboration with suppliers in the automotive industry, whereas Fine (1998) observed the opposite in the electronics industry. This contradiction can be resolved, however, if we take innovativeness into account.

The comparison between the automotive and electronics industry provides an explanation. Doran *et al.* (2007) focus on the trend towards modularization that is visible in the car industry. The most popular example of this trend is the Smart car. From the viewpoint of the car manufacturer, it is a platform innovation. Fine (1998), however, describes an industry where products are highly modular and the interfaces between modules are stable and well-defined (*e.g.*, Fine 1998; Sturgeon 2002). In this industry, innovation rather leads to derivative products. Single suppliers develop and manage innovations without interfering with others. Thus the change in supply chain configuration and collaboration is not too strong when a new product is introduced. Only with the introduction of a new standard (high innovativeness level), can a bigger change in the supply chain occur. In the automotive industry, however, car manufacturers should collaborate intensively with their suppliers to produce innovations and to react to modularization trends. Figure 4.3 shows the positions of both industries in the previous matrix.

Modularity	Higher	*lower effect*	*Medium effect*
	Lower	*medium effect*	*higher effect*
		Low	High
		Innovativeness	

Figure 4.2 Expected effects on supply chain complexity depending on modularity and innovativeness

Modularity	Higher	*Electronics industry*	
	Lower		*Automotive industry*
		Low	High
		Innovativeness	

Figure 4.3 The actual relative effects described in the electronics and automotive industries

4.3.4.3 Variety

Variety is widely recognized to increase SCM complexity. For instance, variety leads to a loss in scale economies because volumes are split among more products.

High variety firms experience higher demand uncertainty and forecast errors than low variety firms (Abdelkafi 2008, Pil and Holweg 2004, Da Silveira 1998).

A multiple case study research conducted by Tachizawa and Thomsen (2007) in different industries highlights that firms use flexible sourcing strategies with a larger supply base, a lower level of supplier integration, and faster supply network re-design in low commonality, high demand volatility, and high volume and mix uncertainty contexts. It should be noted that Tachizawa and Thomsen (2007) disregard product modularity and innovativeness. Given the same replenishment lead time, the proliferation of end items increases the levels of stock. To reduce inventory costs, the best performing firms in the US bicycle industry locate suppliers of high variety components next to the target market, thus increasing responsiveness to demand. However, the manufacturing of components whose production costs are high is centralized (Randall and Ulrich 2001). Therefore, supply chain configuration complexity increases. The supply chain coordination tools required to manage a high variety environment are more complex. Kaipia and Holmström (2007) propose differentiated planning approaches for firms with a large product portfolio, as this kind of firm face more intricate supply chain planning problems.

Proposition 5 (P5): Variety increases the complexity level of supply chain configuration and collaboration.

Proposition 6 (P6): Variety increases the complexity level of supply chain coordination.

Abdelkafi (2008) analyzes variety-induced complexity in mass customization and studies the complexity reduction potential of different variety management strategies. The introduction of an innovation in the form of a new product line can result in additional variety, and so additional variety-induced complexity. This may negatively impact the effectiveness of the variety management strategies, which aim to increase supply chain performance. It is expected that the complexity of a mass customization system will be less sensitive to variety if this variety moves under a certain limit level. Blecker and Abdelkafi (2006) believe that after going beyond this limit complexity will increase exponentially, leading to a system that is unpredictable and difficult to manage. This thesis boosts the importance of anticipating the effects of dynamic variety on the supply chain.

4.3.4.4 Supply Chain Complexity and Performance

The tools for planning and operatively managing the supply chain should be chosen on the basis of supply chain design decisions. For instance, information sharing tools should be used to integrate clients and suppliers (Hill and Scudder 2002).

Proposition 7 (P7): Supply chain configuration and collaboration complexity increase the level of supply chain coordination complexity.

The HP case study shows that in order to fully exploit the potential of postponement strategy to achieve mass customization benefits, the position of the order penetration point and the modularity of the product should be concurrently defined (Feitzinger and Lee 1997). In the automotive industry, the empirical work by Jacobs *et al.* (2007) shows that modularity affects supply chain efficiency and flexibility. This impact is mediated by supplier integration, *i.e.*, supplier development, JIT purchasing, and the level of partnership. The empirical survey bySelldin and Olhager (2007) shows that at the supply chain level, the alignment of the product and supply chain design is significant for supply chain responsiveness, delivery dependability, and supply chain efficiency. Salvador *et al.* (2002) notice that the right combination of product modularity, product variety, and sourcing strategy (related to supply chain design) enhances operational performance.

On the basis of these considerations, the following can be stated:

> *Proposition 8 (P8): Supply chain performance depends on supply chain design decisions, and product modularity, product variety and innovativeness.*
>
> *Proposition 9 (P9): By matching product modularity, product variety, innovativeness to supply chain design planning and management, the supply chain performance is enhanced.*

4.4 Conclusions

This chapter presents a framework for NPD-SCM alignment that can be applied in a mass customization context. It suggests that the matching of supply chain configuration, collaboration, and coordination with product features supports firms that want to offer customized products at high efficiency and responsiveness. The alignment framework includes modularity, dynamic variety, and innovativeness. We believe that the optimization of business processes for a given static variety without considering the dynamic impacts of new product introductions negatively affects operations. Indeed, a supply chain system that is optimal for a given variety does not necessarily stay optimal when the level of variety changes and when a highly innovative product is introduced. A case study supports this idea. Key metrics have been used to evaluate dynamic variety and its impacts on supply chain operations.

We analyze the relationships between supply chain-related variables and product features and then formulate propositions. Propositions are based on theoretical argumentation and the comparison of published case studies. We show that the consideration of innovativeness and dynamic variety can justify decisions that contradict the managerial guidelines recommended by modularity research in mass customization. Further research should be devoted to the validation of propositions and better understanding of the dynamics of NPD-SCM alignment in mass customization settings.

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Chapter 5
Managing Technological Innovations Affecting Product Complexity, Modularity, and Supply Chain Structure

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Abstract Modularity is one of the most relevant paradigms in manufacturing as it has made mass customization possible through the introduction of postponement and through the effective management of product complexity. Hence, the study of the relationships between mass customization, modularity, technological innovations, and the supply chain still has elements that can be used to extend existing knowledge in the field. This chapter provides an insight of the management of technological innovations using modularity to provide customized products. The cases in the automotive industry addressed reveal that the capability of handling a modular architecture in a complex product can offer an infinite number of bespoke configurations with the sources of innovation for modular architectures located within the firm. The findings support the use of a modular architecture to assist in the introduction of technological innovations with a minimum disruption to the supply chain.

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Abbreviations

OEM	Original equipment manufacturer
PC	Personal computer
SVI	Small vehicle integrators
USB	Universal serial bus

5.1 Introduction

The objective of the work presented in this chapter is to understand the use of modularity to handle product complexity as a result of technological innovations, especially in those sectors where economies of substitution, upgradeability, and inter-changeability have been achieved. In recent years the need to manage technological innovations in an efficient way has driven organizations to pay attention to modularity, supply chain management, and product complexity. Modularity is a well acknowledged practice used to address the operational issues raised by mass customization (Salvador *et al.* 2002). The concept of mass customization has been defined as the ability to provide customized products or services through flexible processes in high volumes and at reasonably low costs (Da Silveira *et al.* 2001). The resulting tradeoff between product variety and operational performance may be mitigated by organizations deliberately pursuing modularity in designing their final product architectures, allowing them to obtain final product configurations by mixing and matching sets of standards components (Salvador *et al.* 2002). Huang *et al.* (2007) state that under the modular product architecture, platform products normally have a fixed number of modules with customization being achieved through variant modules to choose among a set of given module options.

It has been through the introduction of postponement and the effective management of product complexity that modularity has reached a top place among practices adopted by firms in diverse sectors. In general terms, modularity permits the management of complexity of products to attain sustainable growth (Christensen 1998; Baldwin and Clark 1997, 2000, Hsuan 2003; Sanchez and Mahoney 2003, Mahoney 2004). For Baldwin and Clark (1997) the successful implementation of a modular architecture depends upon key factors such as the architecture definition, the interface between core-module definition, and standard modules.

The adoption of modularization and the opportunity it gives us to handle mass customization can have an impact on customer satisfaction, especially for products with high innovation content. For example, White (1996) mentions quality, delivery, dependability, cost, flexibility, and innovation as variables that influence customer satisfaction. On emphasizing the importance of competitiveness, Koufteros *et al.* (2002) define a series of constructs across industries to measure flexible product innovation, quality, delivery dependability, competitive price, and premium price. The results of their work based on 244 firms across four industries suggest significant relations among the competitive capabilities and profitability. Furthermore, it is possible to find that several firms in different sectors have embraced modularity in their processes to give more benefits to their customers. Typical examples found include the consumer electronics, personal computers (PC), and automotive sectors. In the PC industry, Dell uses modularity as an effective way to gain an edge over the competition. Dell Computer has been capable of offering its customers affordable customized equipments in a timely fashion with the latest technological innovations available.

A firm's mass customization capability has implications to its supply chain, as this is affected by the availability of technological innovations in modular architectures. In several manufacturing sectors including consumer electronics, the aerospace and automotive industries to mention just a few, a significant number of technological innovations have been developed by key suppliers. In the view of Hsu *et al.* (2009) a firm that actively involves key suppliers in design and development efforts must effectively manage its supply chain. Hsu *et al.* add that sharing information, technology, and risk are contingent on having sound relationships with potential partners; hence, the effective incorporation of supplier parts into new products requires careful evaluation of how they will interface. On the other hand, as a strategy for value creation, modularity has been acknowledged as a systemic innovation (Nystrom 1990, Birchall and Green 2006), where autonomous innovations are held at sub-system level components that are interchangeable and upgradeable through the effective implementations of interfaces.

Academics and managers acknowledge the importance of taking on board concerns related to the supply chain during the product and process design phases in order to operate a more efficient supply chain (Simchi-Levi *et al.* 2003). This statement acquires more relevance when the introduction of innovative technologies can result in higher levels of complexity added to a product. Hence, the advantages associated to technological innovations have to permeate to the structure of the supply chain in order for it to transform itself to manage additional complexity. The supply chain relation to modularity offers significant research opportunities, as Hsu *et al.* (2009) add that the aspect involving supply chain management practices on operation capability and firm performance is limited and inconclusive. To emphasize the role of the supply chain as something that has been around for a while, it is worth mentioning that in the 1980s Porter (1985) indicated that value creation associated to the operations capability of a firm can reach customers and suppliers as well.

In addition to the challenge represented by managing a modular supply chain, the involvement of suppliers in defining module characteristics necessarily brings to consideration the element of product design and development. The study by Randall *et al.* (2003) study on the relationship between initial supply chain investments during market entry and product demand found that firms account for characteristics such as market growth, product variety, contribution margins, and uncertainty when first considering supply chain investments. Other studies have focused on demonstrating that early supplier involvement in new product development leads to significant improvements in cost, quality, and cycle time across the supply chain (Ragatz *et al.* 2002). Long term relationships among firms, customers and suppliers using networks to facilitate information sharing would become widespread in the context of product innovation and supply chain management (Cox *et al.* 2002). Also, research undertaken has found that supplier involvement in new product design and development is a source of competitive advantage (McGinnis and Vallopra 1999) or that the intensity of new product development and revenue generated are directly related to global sourcing levels (Ettlie and Sethuraman 2002).

The methodology employed in the work presented in this chapter is characterized by the use of a qualitative investigation on the relationships between modularization, the introduction of technological innovations, mass customization, and supply chain management. The methodology employed helps to provide an insight into the management of technological innovations using modularity to manufacture customized products and the automotive industry to drive its conclusions. Along with aerospace, the automotive sector is a major industry where a significant number of technological innovations continuously take place. Motor vehicles are complex products themselves, as they are made of thousands of different parts and components. Overall, a motor vehicle is characterized by being made of independent modules; its manufacturing involves a complex assembly process and its supply chain is multi-tier in its own right. Also vehicle manufacturers have a major economic impact in the regions where their plants are located.

Every modular product that has a semi-open or open architecture also has a critical module that drives the overall product architecture. In PC architecture, for example, the speed of the microprocessor determines the pace of the evolution of the PC (Gawer and Cusumano 2002). In several motor vehicle applications, a key element that determines technical evolution is the engine (Van den Hoed 2004).

Based on a series of cases in the automotive sector, the main contribution of this chapter is in terms of highlighting that innovations are embedded in modular systems where industry-wide accepted system standards are likely to appear. This consequently promotes changes to the dynamics of competition and redefines the relationship between product architects and system designers. The resulting effect necessarily reaches to the supply chain, challenging typical design and management of the supply chains. This fact, plus that of technological uncertainty and the costumer expectation of customized products requires tackling by managers in a particular way.

The next section reviews modularization, customization, and technological innovations in the automotive industry by giving examples of technologies that a few years ago were under development and now have become standard equipment in most vehicle applications. The work presented in this study uses the motor coach/transit bus sector because of the suitability offered to study the interactions between modularity, mass customization, technology innovation, and supply chain management. The heavy duty transport industry (coach/bus) is an ever evolving competitive environment in which firms tend to compete in two value creation strategies fronts at the same time but, with different time frames. The first of these strategies is about creating value through mass customization, which refers to the fact of developing custom made vehicles in relatively large numbers but in an economically feasible manner. The second is about the establishment of market dominance in the short and medium run; by quickly adapting their product architecture to accommodate new technologic developments created by key automotive suppliers; this through the effective management of modular sub-system interfaces. This characteristic (modular product architectures) enables motor coach and bus manufacturers to profit from mass customization, and if innovations are embedded in modular systems, industry-wide accepted system standards are likely to appear. As a result, changes to the dynamics of competition and redefining the relationship between product architects and system designers are promoted.

5.2 Modularization, Customization, and Technological Innovations in the Automotive Industry

One key industrial sector that has benefited from the use of modularization is the automotive industry. In recent years, the automotive industry has adopted modular architectures. It has been able to provide higher levels of customization and has introduced significant technological innovations to its products; its supply chains are among the most complex and efficient in the world. In this sector, characterized by the use of modular architectures, product variety is achieved through the effective management of possible combinations of modular components; thus, modularization is an effective tool to increase flexibility (Baldwin and Clark 1997 2000, Garud and Kumaraswamy 1995, Garud *et al.* 2003). During the product development stage this also increases the coordination among components developers within a specific architecture value network. However, there can be difficulties in running modularity, as the works by Iansiti (1998) and Chesbrough and Kusunoki (2001) claim that modularity may represent a burden difficult to bear for companies that do not acknowledge the limitations of modular architectures.

Modularity has significant implications to the automotive sector for several reasons. Authors such as Veloso and Fixson (2001) argue that a modular architecture modifies the balance of power in the supply network of the OEMs by transferring bargaining power to automotive suppliers. This assumption is based on the premise that all modular architectures used by major OEMs are designed to face similar conditions and similar users, which results in similar performance requirements for all of them and ultimately leads to similar solutions. Thus, automotive suppliers can use the principle of inter-changeability to achieve economies of substitution by supplying the same or slightly modified components to several automotive modular architectures. Without any doubt, modular design and constant innovation are closely linked to the dynamics of the modern auto industry. Open architectures, well defined standards, and the effective management of component (modules) interfaces have the potential of being beneficial to OEMs. Modularization in the automotive industry covers product, production, and networks through the dynamic interaction of system integrators and other suppliers (Takeishi and Fujimoto 2003).

The adoption of modularity has motivated authors such as Helper *et al.* (1999), and Cammuffo (2000) to propose that future vehicles will consist of self-contained functional units with standardized interfaces within one or more standardized product architectures. Thus, cutting edge technological developments in modular designs can lead to high levels of supply chain complexity and high degrees of value creation activities for OEMs. Furthermore, Tidd *et al.* (2005) argue that increasing complexity of product architectures in modular architectures is a direct consequence of the increased specialization of suppliers/vendors. Brusoni and Prencipe (2001) clearly acknowledge the necessity of a system integrator that comprises the capabilities necessary to understand independent technological developments.

An effective way to appreciate the effects of collaboration between OEMs and suppliers to introduce new technological advances using modularity principles can be seen in real automotive applications. The next three examples compiled by Newlaunches (2006) show three technologies that were under development in 2006 but were options available in motor vehicles in 2008.

1. External audio integration. Three years ago, automakers became busy trying to make their vehicles compatible with the iPod which is the world's favorite MP3 player. Today, Volkswagen has integrated an iPod dock as well as USB and FireWire jacks for connecting other MP3 players to the dashboard of some of its vehicles.
2. Volvo fully automatic brakes. The Volvo S80 comes with a collision warning system with brake support where a red light flashes and a buzzer sounds if the driver is about to run into another vehicle. If the driver does not stop fast enough the vehicle automatically increases the brake pressure.
3. BMW, Toyota, and Volkswagen Auto Park. Automakers BMW, Toyota's Lexus, and Volkswagen have developed a technology that finds a space large enough and then does the parking of the vehicle. Sensors automatically measure a row of parked cars and alert the driver when there is a space large enough for the vehicle and then the "auto park" control of the vehicle parks it automatically.

The above paragraphs identify modularity, technological innovation, and supply chain management as interrelated elements that influence the capability of organizations to offer customized products that meet the opportunities presented by unique changing customer needs. From the literature reviewed and the illustrative examples it becomes evident that effective mass customization would not be possible in the absence of modularization. Furthermore, the introduction of technological innovations is facilitated through the use of modularity. Because the use of modularity is likely to involve dealing with suppliers, the supply chain inevitably emerges when dealing with mass customized products that incorporate technological innovations.

The study described in the next sections of this chapter looks at the automotive industry, in particular the motor coach and transit bus sectors. Interviews with managers as well as collection of data sets are used to identify the shaping role of technological innovations affecting automotive modules, the capability to maintain higher levels of customization, and the eventual effect it has on the efficiency of the supply chain.

5.3 Modularity and Mass Customization in Motor Coaches and Transit Buses

There is common misconception that truck and bus developers lag behind passenger car manufacturers regarding technology adoption. However, the truth is that manufacturers of Classes 6, 7, and 8 vehicles (industry notation) in the bus industry have mastered modular architectures and interfaces in a better way than OEMs of passenger cars. Still, this goes beyond the mere implementation and management of modular architectures.

The effective management of modular architectures by body builders can ensure customer satisfaction by allowing architectural product modifications that OEMS would find impossible in passenger cars. This phenomenon is explained by the mechanics of the motor coach/transit bus industry; in which typically the end customer can actually steer vehicle configuration according to its very own specifications. Also in this industry another steering force of product configuration is represented by key suppliers who by introducing added complexity to modular systems, force vehicle integrators (bus and coach manufacturers) to quickly adapt new technologies and redesign their existing product(s) architectures in order to accommodate the changes introduced. Figure 5.1 depicts the hierarchy of steering considerations (or layers) when designing a product architecture for long distance motor coaches and transit buses.

The redefinition of the evolution of technology in the automotive industry is seen in the long distance coach industry mainly as the disintegration of the struc-

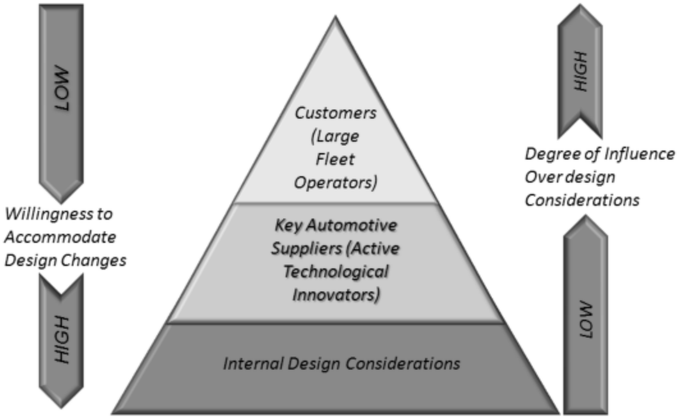

Figure 5.1 Product development steering hierarchy for the motor coach/transit bus industry

ture of value network toward a more customer-based industry; hence conforming to the principles of mass customization. This industry is divided mainly into two tiers. The first tier is represented by international OEMs such as Volvo, Mercedes–Benz, MAN, and Scania and in minor scale MCI coaches of the US. These manufacturers are able to produce a complete motor coach (chassis and body) while offering to their customers complete vehicle solutions. The second tier is represented by body builders whose core product is the development of the body that the vehicle uses.

Companies such as Marcopolo, Busscar, and Neobus/San Marino from Brazil and Sunsundegui and Irizar from Spain, among many others, represent body builders with a global scope. Body configurations are offered to a large assortment of vehicle chassis, therefore any given body is able to fit almost any chassis available in the market. This situation has forced body builders to effectively manage several interfaces among many core vehicle modules, *e.g.*, as different types of chassis architectures. Figure 5.2 depicts the mass customization nature of the industry.

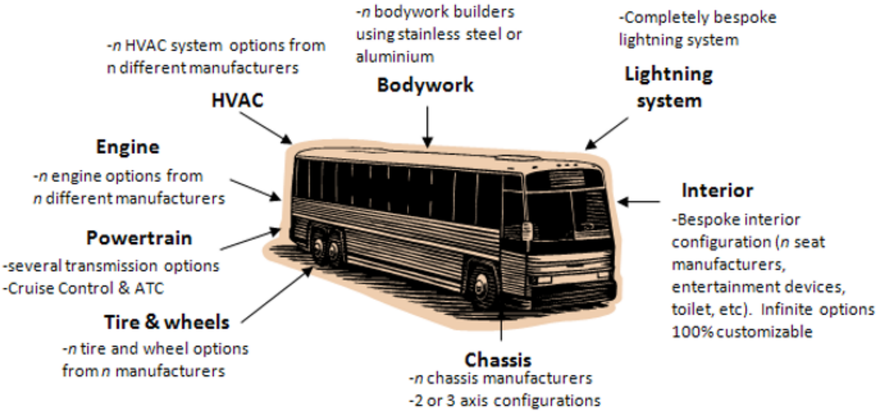

Figure 5.2 Depiction of motor coaches/transit buses industry disintegration

Thus in Class 8 heavy duty vehicles, the ultimate benefit of modularity, economies of substitution, upgradeability, and inter-changeability (Garud and Kumaraswamy 1995) are achieved, not by the architecture designer (such as the OEM or body builders) but by the customers, who are usually large fleet operators with sufficient leverage power to modify vehicle configurations and interchange body modules with chassis modules at their will.

This adds to the fact that major automotive suppliers for Class 8 vehicles (companies like Voith, Allison, ZF, Hella, Arvin-Meritor, TRW, SKF, *etc.*) are technological innovators with proprietary applications included as sub-system components in several automotive modular architectures. Typical sub-system components include automatic transmissions, lighting systems, braking, exhaust systems, *etc.*

Figure 5.3 describes the interactions between the parties involved in the motor coach/transit buses sector; the interaction between key automotive suppliers and vehicle integrators can be depicted as a number of links representing the organizational and business outcomes of the interaction between OEMs (including small vehicle integrators), body builders, and key automotive suppliers.

The link *strategic knowledge* shown in Figure 5.3 represents the capabilities, non-tangible assets, and tacit knowledge necessary to design, validate, assemble, and economically build feasible coaches at a mass production scale. This strategic knowledge transfer has enabled body builders to act as knowledge accumulators, since they have been gathering knowledge from multiple sources (primarily from OEMs). The link *strategic leverage* represents the benefits that OEMs obtain from participating in niche markets that are not economically feasible under mass production premises. The *strategic leverage* enables OEMs to create value through savings in economic and human resources, more specifically in product development (design and validation), and above all in product manufacturing. The link *operational efficiency* represents the benefits of modular components utilization provided by automotive suppliers, which ultimately enable body builders to actually be so flexible. The link *network expansion* represents the effects of network externalities, which involve the utilization of modular sub-systems with proprietary technology created on automotive suppliers' products and utilized by body builders. According to Figure 5.3 all interactions between automotive suppliers take place on a higher ground by the effective management of modularity. The interactions between body builders and OEMs are understood under the premises that they mainly concern the management of the vehicle architectural openness.

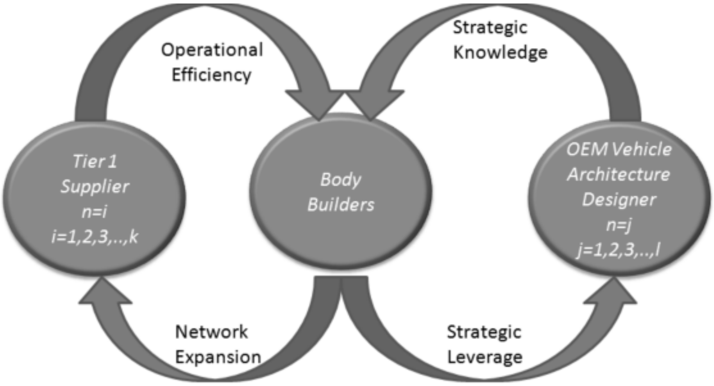

Figure 5.3 The topology of the motor coach/transit bus industry

5.4 Methodology

Within the automotive sector, an example of the use of modularity to handle product complexity as a result of technological innovations is the production of heavy duty vehicles, where economies of substitution, upgradeability, and inter-changeability are achieved to meet the requirements of customers who are able to modify the configuration of a vehicle and interchange body modules at their will (Mondragon *et al.* 2009). Body builders for motor coaches and small vehicle integrators (SVI) – such as North American dedicated transit buses manufacturers – represent the closest industrial practice to “mass customization” through the effective management of modular architectures, which take place as flexible interfaces between the loop comprising sales-purchasing-engineering/validation-manufacturing and the correct management of non-dedicated equipment. Body builders that put these elements in practice can ensure customer satisfaction by allowing architectural product modifications that would be impossible for OEMs of passenger cars to achieve (Holweg and Pil 2004).

The study described in this work is qualitative in nature. It has been highlighted that a qualitative study must be flexible enough to allow unforeseen types of information to be recorded (Seaman 1999). The method employed during the data collection included the use of semi-structured interviews, which has become a well acknowledged tool in the field of operations management (Flynn *et al.* 1990). The notes from the semi-structured interviews were supported by observations and documentation of the systems evaluated as described by DeSanctis and Poole (1994) and Holweg and Pil (2008). Semi-structured interviews include a mixture of open-ended and specific questions, designed to elicit not only the information foreseen, but also unexpected types of information (Seaman 1999).

The case study methodology (such as the one employed in this research work focusing on the heavy duty transport industry) has been thoroughly explained by Yin (1994) and it is a technique commonly utilized in operations management research. Generally, the case study has some longitudinal dimension since it is conducted over a period of time. A ramification of the case study is the site visit. Seaman (1999) has provided a detailed description of the use of case study and site visit. According to her, a site visit is planned to obtain first-hand information from tours of specific facilities and services, interviews with individuals or groups, or observations of specific activities at the site. In addition, the site can be used to obtain reports, brochures, and examples of products or services made available at the site. Site visits enable the opportunity to obtain first-hand information about users or activities in a particular setting. Another benefit is the ability to evolve the data collection strategies on site, depending on the topics that the evaluator determines are important to probe for obtaining additional information.

The growing importance of modularity and its repercussions on the supply chain suggest the need for a deeper understanding that can be used to address how technological innovations affect main business aspects of modern day organizations. At present, the vast amount of studies on modularity available in the literature can be classified into two fields: supply chain management and value creation and growth (Takeishi and Fujimoto 2003). In the following sections, elements of both fields are addressed. The next section introduces the development of modular systems for motor coaches/transit buses.

5.5 Modular Systems Development for Motor Coaches/ Transit Buses (Heavy Duty Vehicles)

Every modular product that has a semi-open or open architecture also has a critical module that drives the overall product architecture. In the PC architecture, for example, the speed of the microprocessor determines the pace of the evolution of the PC (Gawer and Cusumano 2002). In several motor vehicle applications, a key element that determines technical evolution is the engine (Van den Hoed 2004).

The motor coach/transit bus represents a suitable case to study the interactions between modularity, mass customization, technology innovation, and supply chain management. The heavy duty transport industry (coach/bus) is an ever evolving competitive environment in which firms tend to compete on two value creation strategy fronts at the same time but, with different time frames. For example, first, by creating value through mass customization, which refers to the development of custom made vehicles in relatively large numbers but in an economically feasible manner. Second, it refers to the establishment of market dominance in the short and medium run; by quickly adapting their product architecture to accommodate new technologic developments created by key automotive suppliers; this is done through the effective management of modular sub-system interfaces. This characteristic (modular product architectures) enables motor coach and bus manufacturers to profit from mass customization, and if innovations are embedded in modular systems then, industry-wide accepted system standards are likely to appear. As a result, it promotes changes to the dynamics of competition and redefining the relationship between product architects and system designers.

The companies that participated in the case study are major manufacturers of chassis for motor coach and transit buses. The individuals interviewed include a senior executive of a motor coach/transit bus manufacturer, the engineering director of a motor coach, global bus, and truck manufacturer, and the sales vice-president of a global bus manufacturer. For confidentiality reasons the names of the three participating companies in the study are kept anonymous. One of the co-authors of this chapter has extensive in-depth knowledge of the industry after years of working as a design engineer and executive, and as a result it was possible to give the interviewees more freedom to expand their answers. The questionnaire instrument used during the semi-structured interviews is included in Appendix A. The questions cover aspects such as needs and aims of customers when they purchase a bus/coach, expectations regarding technological innovations that can be purchased as well as options available, capabilities to succeed in the market place, and customization capabilities and implications to the supply chain. During the interviews it was also possible to access data sets, reports, and brochures from each of the companies interviewed.

5.6 Findings

The research work undertaken has found a set of architectural themes that are key elements to justify the implementation of mass customization approach and its impact on the vehicle supply chain. The themes included are: overall control on product architecture, autonomy of modular suppliers, and sources of innovations. Table 5.1 summarizes the research themes employed.

The following transcripts were summarized after interviewing the executives and engineering directors, from bus and coach manufacturers with global scope, who took part in the study.

Table 5.1 Research themes investigated and associated original expectations

Research theme	Original expectation
Who control the overall product architecture?	Vehicle integrator controls architecture. Originally it was expected that vehicle integrator would control architecturally complex modules
Degree of autonomy of development for modular suppliers	Unidentified degree of autonomy
Sources of innovation	Internal. But with unidentified value creation processes

5.6.1 *Control of Product Architecture*

Concerning the control of the product architecture the research undertaken has found that contrary to our original expectation, integrators control architectural and design considerations only to a certain degree. However, the most important architectural controller and technology enablers are clients, normally large bus/coach operators, who exercise leadership through their financial might and technical savvy. As expressed by a senior executive of a motor coach/transit bus manufacturer during the interview:

> Clients do exercise control over architectural decision not only by setting stringent performance goals on the vehicle, sometimes they very actively participate in architectural decisions and styling clinics.
> Clients are very knowledgeable buyers, they are indeed able to modify vehicle architecture and specs', if we do not yield to their suggestions they simply will find someone else that will do.

5.6.2 *Autonomy of Suppliers*

Concerning the degree of autonomy of suppliers, the research shows that technological independence of suppliers is plausible for mature and low tech architectures. According to the findings from the interviews, motor coach/transit bus architectures are so stable and their modular components are so well defined that it enables the entrance of automotive suppliers with total independence from the system integrator. As stated by a senior executive of a global bus, coach, and truck manufacturer:

> Technological stability of the product platform enables a steady growth on individual systems developers, thus forcing suppliers to compete on better technological advancements and price.
>
> Some suppliers are so strong that they develop strong ties with our customers, thus persuading them to include their modular systems in our vehicle architecture, forcing us to develop interfaces that enable proper vehicle performance.

5.6.3 Sources of Innovation

The sources of innovation for this type of modular architecture are internal. Innovation at the system integrator level is reflected through the capability to quickly adapt to technological changes on individual modular systems, but above all, the value creation strategy, mainly resides on effective managerial approaches to tackle manufacturing complexity and large product variety and customized vehicles. Essentially, manufacturers achieve this through effective project management approaches, manufacturing excellence, and customer management. Another senior executive of the same global bus and coach manufacturer states:

> The ability to manufacture highly customized vehicles in small numbers (when compared to cars) in an economically feasible manner is vital for surviving in this industry.
>
> If we lack (the vehicle integrator) the knowledge and capabilities to integrate unknown technologies in modular systems, suppliers will partner with us to successfully integrate their technology in our architecture.

The interviews with the directors confirmed the complexity of the relationships between different players when it comes to dealing with defining modular architectures, introduction, and availability of technological innovations, customization levels, input from customers, and suppliers' expertise. The findings of the study are summarized in Table 5.2.

The supply chain of heavy duty transport vehicles (motor coach/transit bus) is perhaps one of the most advanced supply chains in terms of being capable of handling a modular architecture in a complex product that enables the possibility of offering an infinite number of bespoke configurations according to customer needs. In the motor coach/transit bus sector, the capacity of the supply chain to handle technological innovations can be attributed in part to the location of its decoupling point. Hence, technological innovations can be introduced in a specific module because modularity is in place. In the absence of modularity the supply chain is at risk of disruption. Figure 5.4 illustrates the supply chain of a motor coach supply chain, which in terms of units produced represents a low to medium volume supply chain.

Table 5.2 Findings from the case study

Research theme	Original expectation	Observation
Who control the overall product architecture?	Vehicle integrator controls architecture. Originally it was expected that vehicle integrator would control architecturally complex modules	Client. The ultimate controller of vehicle architecture are clients–usually large fleet operators–through financial might and technical savvy
Degree of autonomy of development for modular suppliers	Unidentified degree of autonomy	High. Innovative developments are mainly produced by autonomous research and commercialization by suppliers
Sources of innovation	Internal. But with unidentified value creation processes	Internal. Value is created by systems integrators through effective project management techniques, agile manufacturing, and with quick adaption of technical competencies

In Figure 5.4 the modular capabilities found in the supply chain of motor coach/transit bus vehicles enables the introduction of technological innovations upstream in the supply chain. For example, the diagram in Figure 5.4 illustrates the case of electronic engine management control modules that can be manufactured and fitted to powertrains comprising several engine and transmission configurations. Later, these engine and transmission configurations are fitted to an unspecified number of chassis arrangements, which are then transformed by a bodywork builder who attaches a specific body to the chassis. The bodywork builder may put a bespoke interior configuration that may include the latest satellite navigation and entertainment systems. The modular architecture adopted in motor coach vehicles means that technological innovations can be introduced with a minimum disruption to the structure of the supply chain. Then, it may be possible to have motor coach options that include external audio integration (iPod dock) to each passenger seat or perhaps include a fully automatic braking system, making motor coaches and transit buses safer.

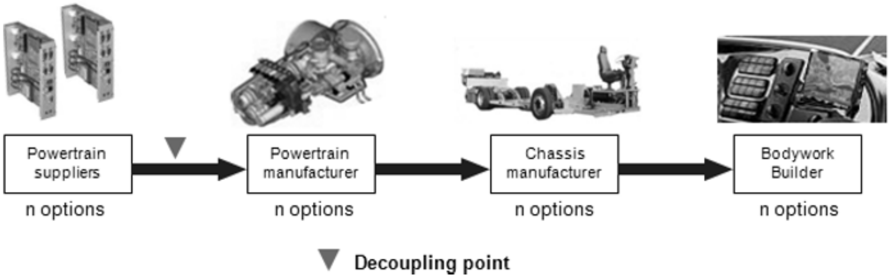

Figure 5.4 Motor coach supply chain

5.7 Conclusions

The automotive industry still represents an industry where a significant number of technological innovations are tested and first introduced to customers. It has become clear that modularity is a key source of competitive advantage as it enables high levels of customization and handling of technological innovations.

For industries where customers require highly customized goods, modular integration capabilities not only imply the ability to mix and match modular components, but to modularize value creation processes such as value chains and product integration capabilities, specifically when technological innovation disrupts the knowledge integration capabilities of the system integrator (*i.e.*, body builder or OEMs).

Specifically, in this industry value creation is achieved by customizing products (vehicles) through flexible processes in high volumes and at reasonable low costs. Therefore, innovation and value creation takes place in the organizational realm for these manufacturers; which in order to excel and create value have to master effective project management techniques, agile manufacturing competencies, and be keen to adopt new unknown technologies developed by bigger and stronger firms (automotive suppliers).

It has been previously mentioned that if innovations are embedded in modular systems, then industry-wide accepted system standards are likely to appear, resulting in support to the dynamics of competition by redefining the relationship between product architects and system designers. This effect necessarily reaches the supply chain, challenging typical design and management of automotive supply chains. This fact, plus that of technological uncertainty and the costumer expectation of customized products requires tackling by managers in a particular way.

Modularity is a business initiative that has a supply chain-wide scope and implications. Hence, related suppliers and customers, as well as the OEM embracing modularity, are likely to be impacted by the adoption of technological innovations. In a state like this, it is expected that technological innovations will affect the structure of the supply chain by modifying it in a way that enables handling the changes introduced through modularity.

In reference to the applicability of this study to other industries, it is well acknowledged that the main stream of car manufacturers is striving to introduce more customized products. Holweg and Pil (2004) documented modularization practices employed by car manufacturers. However, we foresee very similar dynamics of product customization and management of modular architectures to the ones described in this study in industries such as aircraft manufacturing (especially with respect to interior cabin design), recreational vehicles manufacturing, motor homes manufacturing, aircraft simulator manufacturing, and others.

Appendix

These questions were developed in order to understand the dynamics of value creation and technological diffusion in the motor coach and transit bus industry.

1. Could you concisely define the needs and aims of your customers when looking for a vehicle (bus or coach)?
2. Are customers thrilled by technological innovations presented by your company?
3. Do customers are willing to pay for technological innovations that increase overall, vehicle performance? Or, are they more concerned with cost-saving improvements?
4. Do corporate strategy and guidelines from the head office encompass and match the expectations of your client base (locally wise speaking)?
5. What are the innovations more frequently sought and implemented at your organization: incremental (*e.g.*, cost reductions; product improvement, solutions to quality issues, improvement to production processes, successful implementation of organizational changes) or radical (introduction of new technologies embedded in the vehicle)?
6. To what extent do your internal processes cope with the firm aim for innovation? (Is innovation internally hindered by internal processes stiffness?)
7. What are the core capabilities that a bus and coach manufacturer must possess in order to succeed in the market you compete in?
8. According to the answer provided above, does your company have those core capabilities to successfully compete in the market? If not, is there a plan or road map for acquiring those capabilities?
9. Could you mention the advantages of producing and developing internally chassis for buses and coaches, rather than produced chassis based on the integration of available components supplied by Tier 1 suppliers?
10. Could you mentioned the advantages of providing complete solutions (chassis and body from one brand), rather than providing either chassis or bodies separately?
11. Does your clientele require customized products? If yes, do your internal processes enable the company to comply with your clients' requirements?
12. What are the roles that suppliers play in this industry? Are suppliers capable of bargaining directly with the end customer (vehicle operator) and forcing the redefinition of vehicle architecture?
13. What are the factors that determine the degree of flexibility while customizing buses or coaches?
14. Do new technological developments of suppliers disrupt the available vehicle architecture?
15. Do failures and recalls in specific systems provided by suppliers (such as entertainment systems, for instance) have a negative impact on the overall quality perception of your brand?

16. According to your perception, do you see a trend where innovation in coach and body building is set by critical suppliers? If yes, would this compromise achieving strategic goals in the future? Would this create any unwanted dependencies toward critical suppliers?
17. Could you mention some of the most important technological innovations that are being developed by OEMs and are suitable for implementation for buses and coaches in the short, medium, and long run? How would the company market these developments?

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Chapter 6
The Platform Formation Problem

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Abstract Today's globally competitive world of manufacturing requires participating firms to introduce an increasing number of products with shorter life span, at a lower cost, in an environment where demands are uncertain and with shorter lead times to fulfill those demands. One approach towards meeting these demands is the use of mass customization, specifically the platform based design and production strategy. This chapter presents the platform design problem in which a platform is created with the objective of producing a family of products at a minimum cost. By using the platform every product variant in the family is assembled either directly from its components or from the platform. Three methods for developing such a platform-based strategy are described: design of a single platform, design of multiple platforms, and design of a single platform while considering demand uncertainty.

Abbreviations

BOM	Bill-of-materials
EVPI	Expected value of perfect information
OPL	Optimization programming language
PAR	Part assembly relationship
QFD	Quality function deployment
VSS	Value of the stochastic solution

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6.1 Introduction

In today's highly volatile market there is a growing concern for fulfilling the individual customer wants and needs. "The customers now have plenty of choice … they have become more aware … they select the product that most closely fulfills their opinion of being the best value for the money …" (Hollins and Pugh 1990). Therefore, "customers can no longer be lumped together in a huge homogeneous market …" (Pine 1993); rather this competitive world of manufacturing requires the manufacturer to introduce an increasing number of products with shorter life span and at a lower cost. This requires the producer to continuously search ways to reduce production costs, while still offering attractive products. In the past, a company could capture the market and enjoy high profits by mass-producing a large volume of the same model. Now, the focus in manufacturing is shifting from mass production to mass customization; a trend no longer limited to high value products. This phenomenon is demonstrated by the fact that from 1973 to 1989, there was a 70% increase in the number of car models produced in the US with a commensurate drop in the volume of production *per* model (McDuffie *et al.* 1996). It is thus important to note that there is a distinction between supporting variety and supporting customization as discussed in Simpson (2004), with the platform technology able to support both concepts.

Toward this end, various strategies have received significant attention in the literature and practice including, but not limited to, the use of the concept of delayed differentiation (Lee 1996, Lee and Tang 1997, Swaminathan and Tayur 1998), exploiting commonality at the product design state (Ulrich and Pearson 1993), the use of lean manufacturing concepts (Womack *et al.* 1990), and the product platform strategy (Meyer and Lehnerd 1997).

Due to its advantages, the platform approach has gained acceptance by many corporations as the means to increase their product count without increasing the cost *per* product. Examples of industrial applications of the platform concept include Black and Decker, which applied this idea to its power tool products (Meyer and Lehnerd 1997). Volkswagen used a platform architecture strategy and reduced development and production costs (Wilhelm 1997). Sony applied this approach to its product development process (Sanderson and Uzumeri 1995). AeroAstro Inc. used platform architecture with their multipurpose radio platform and solved many of the communication problems faced by spacecraft system designers (Caffrey *et al.* 2002). HP's Ink Jet Printer platform architecture is rejuvenated constantly and hence the derivative products are constantly upgraded (Meyer 1997). Other examples of manufacturers that have successfully implemented platform based production strategy include Rolls Royce (Rothwell and Gardiner 1990), Boeing (Sabbagh 1996), and Honda (Naughton et al. 1997).

In this chapter, we discuss a platform based approach for the production of a product family. Using this approach, every product variant in the family may either be assembled directly from its components, or from any platform whose component set resembles those required by the product. The methodology seeks to find an optimal platform that will minimize the overall production costs of the products, which include the costs of production, holding cost of unused platform inventory and shortage cost of lost demands of products (if demand is stochastic), while considering the demand of each product type.

The rest of the chapter is organized as follows: Section 6.2 offers a review of the work related to the platform formation problem. Section 6.3 defines the problem along with the description and formulation of three variants: a single platform system, multiple platform solution, and a single platform problem considering demand uncertainty. Section 6.4 presents an example of the stochastic demand case and Section 6.5 provides the conclusion and some directions for future research.

6.2 Background

Ulrich and Eppinger (2003) define a *platform* as a collection of assets, including component designs, shared by multiple products. It can also be defined as a set of shared functionality, components, subsystems, and manufacturing processes across the product family (Robertson and Ulrich 1998).

Various streams of research in the area of product platforms were greatly influenced by contributions from Pine (1993) in the area of mass customization, Meyer and Lehnerd (1997) in the area of platform concepts, and Sanderson and Uzmeri (1997) in the area of managing product families (Allada and Jiang 2002). Krishnan and Ulrich (2001) provide a literature review of the various decisions that take place during the product realization process including when and how to construct a platform architecture.

Simpson (2004) provides an authoritative definition of the platform as a supporting tool for family based production. He also provides metrics and strategies to support platform based production as well as a review of optimization based approaches for platform design. The author clearly distinguishes between variety and customization, but states that "product platforms play an integral role in facilitating the product customization process" while highlighting web based approaches towards platform based customization.

Jose and Tollenaere (2005) provide a literature review of approaches towards platform design. They describe the concept of standardization and modularization as well as various product architectures that support modularity. Allada *et al.* (2006) provide a review of various problem types related to tactical and strategic platform development as well as a review of platform evaluation techniques. Simpson *et al.* (2006) provide an overview of the platform concept, application areas, and ongoing research in academia and in industry.

Research work on qualitative approaches to the platform problem include Maier and Fadel (2001), Dahmus *et al.* (2001), Shil and Allada (2005), and Wilson and Norton (1989). Such approaches can be exemplified by the work of Martin and Ishii (1997, 2002) who developed a conceptual approach towards developing platform architectures utilizing the quality function deployment (QFD) methodology and describing the design-for-variety approach. Similarly, Kota *et al.* (2000), and Park and Simpson (2005) developed methods to assess the design commonality of a product family and the cost of its production.

Platform development is considered a costly endeavor recovered through consumer willingness to pay for the features provided by the platform. An analysis of platform development cost is provided by Krishnan and Gupta (2001). Similarly an analysis of the optimal set of product configurations termed optimal diversity management problem is addressed by Briant and Naddef (2004). A more engineering based approach towards optimal design of platform features is described in Nelson *et al.* (2001), while a more conceptual description of the platform design process is available in Gonzalez-Zugasti *et al.* (2000).

Various quantitative solution methods to the platform optimization problem looked into finding the optimal design parameters that will satisfy the overall function requirements of the product family. These methods include (but are not limited to) the branch and bound algorithm (Fujita and Yoshida 2001), dynamic programming (Allada and Jiang 2002), agent based techniques (Rai and Allada, 2003), simulated annealing (Fujita *et al.* 1999), and genetic algorithms (Li and Azaram 2002, Simpson and D'Souza 2002, 2004). Similarly, Jiao and Zhang (2005) developed an optimization based approach towards allocating product attributes to a product portfolio considering the consumer utility and preferences, and engineering costs and product life cycle. Clearly the overall analysis of a platform based design can be overwhelming considering issues of component design, performance, and quality, as well as suppliers' management, product life cycle, and demand. Practically, due to its complexity the problem is decomposed into smaller segments – one of which is addressed in this chapter.

Platform based architecture is often utilized towards mass customization and can be defined as "building products to customer specifications using modular components to achieve economies of scale" (Durray *et al.* 2000). Some architectures of mass customization emphasize maximizing commonality in design across internal modules, using a product platform with modules as building blocks (Jiao and Tseng 1999). Such an approach utilizes three views of the product: functional, technical, and physical. Mapping between the technical and the physical views implies considering manufacturing and logistics, important aspects addressed in this chapter. The modular structure and technical modules are realized using physical modules as components and assemblies. This arrangement is similar to the typical bill-of-materials (BOM) – since many products can share the same modules, resulting in a polyhierarchical graph (as suggested in this chapter).

Ross (1996) defines five approaches for utilizing the customer voice towards mass customization. At one end the customer can modify core elements in the product while at the other extreme, known as the "high variety push" the manufacturer provides a high variety of pre-designed products. In addition, MacCarthy *et al.* (2003) identify six processes that are essential to mass customization, one of which is "product validation and manufacturing engineering", which is responsible for generating the manufacturing processes and the bill of materials. The methods presented herein fit into the above mentioned approaches.

The platform approach towards product design

Utilizing platforms to assist in product design can be implemented using three modes:

1. scalable platform formation;
2. module based or configuration based platform formation; and
3. combination of both module based and scalable platform formation.

Scale based product family design is a method by which some of the variables in a product family are kept fixed while other variables such as scaling variables, are "stretched" or "reduced" to generate the variants within the product family. Module based product family design is a method by which a product family member is derived by adding and/or removing modules from the platform. This approach, based on the concept of modularity in product design, is more prominent in practice as it allows the platform to leverage for products from different market segments (Baldwin and Clark 1997, Ulrich and Eppinger 2003).

A combination of both module based and scale based platform formation strategies is considered by Fujita and Yoshida (2001).

Optimization based platform formation methods for various objectives

The platform design and selection concept have been used for various objectives such as reducing cost and simplifying the design effort (Simpson 2004), improving life-cycle design (Ortega *et al.* 1999), optimizing production cost or profit, or reducing time to market (Krishnan and Ulrich 2001). Martin and Ishii (1997) proposed methodologies that can help companies to quantify the costs of providing variety and qualitatively guiding designers in developing products that incur in minimum variety costs. Simpson *et al.* (1999) proposed a model that uses the overall design requirements in generating the product platform and resulting product family that best satisfies the overall design requirements. Farrell and Simpson (2001) try to improve response to customers' requests, reduce design cost, and improve time to market for highly customized products by designing product platforms. Sudjitanto and Otto (2001) use a matrix to group modules for platform determination in order to support multiple brands for platform cost savings as well as revenue enhancing. Nayak *et al.* (2002) propose a variation based method for product family design, which aims to satisfy the range of performance requirements for the whole product family.

6.3 Problem Description

In this section a platform is considered to be a set of shared components among multiple products. A product from a product family is produced using a platform by adding or removing some of the components that are assembled using the platform. Figure 6.1 illustrates a hypothetical product family with four products (P_1,

P_2, P_3, and P_4), each consisting of a different collection of components from the set $\{A, B, C, \ldots, H\}$. Suppose a platform for this set of products is as shown in Figure 6.2. In this case P_1 would be created by using the platform, removing G and adding C, and P_3 would be created by removing D and G and adding C and F.

A platform is only justified if the assembly of the components to the platform can be done efficiently using mass production methods. The platform is not a super-set of all the products in the family, for some products parts will be added to the platform while for other products parts will have to be removed. Thus, adding and removing components from a platform to fit a particular product typically cost more than if the component is included in the platform (*via* mass production) and remains there to be used in the product. However, if the component is not required for a particular product, it can be removed and used in a different product.

Each product's bill of materials is considered to be binary. One complicating factor is that while determining the configuration of the platform, the part family relationship must be maintained.

In order to manage the part assembly relationship constraints, a binary part assembly relationship (PAR) matrix for the product family is determined. An element of PAR, $f_{jl} = 1$ represents that component j precedes component l or component j is needed to be present in the platform for l to be included in it, as component l requires j to be assembled to form a platform. As an example, the PAR for the product family shown in Figure 6.1 is shown in Table 6.1.

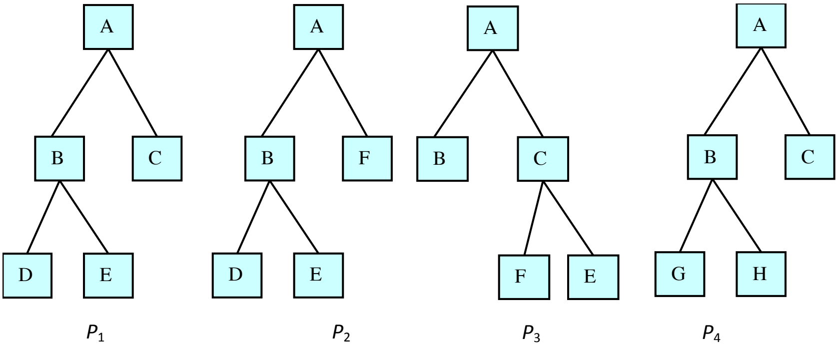

Figure 6.1 Example of a product family

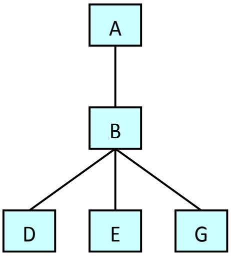

Figure 6.2 A platform for the product family

Table 6.1 PAR for product family in Figure 6.1

	A	B	C	D	E	F	G	H
A		**1**	**1**			**1**		
B				**1**	**1**		**1**	**1**
C					**1**	**1**		
D								
E								
F								
G								
H								

Notations:

K is the set of products in a given product family, $k \in K = \{1,2, \ldots, |K|\}$.
J is the component set, $j \in J = \{1,2, \ldots, |J|\}$.
I represents the platforms, $i \in I = \{1,2, \ldots, |I|\}$; $i = 1$ for the single platform case.
D_k is the demand for the kth product.
C_j is the cost of the jth component (purchasing price).
CP_j is the cost of assembling the j^{t}h component using a platform (mass assembly).
CA_j is the cost of manually adding the jth component to a product ($CA_j > CP_j$).
CR_j is the cost of manually removing the jth component ($CR_j > CP_j$).

V is the product matrix with

$$v_{jk} = \begin{cases} 1 \text{ if product } k \text{ requires component } j \\ \quad 0 \text{ otherwise} \end{cases}$$

f_{ljk} are elements in the PAR such that

$$f_{jlk} = \begin{cases} 1 \text{ if component } j \text{ precedes } l \text{ in product } k \\ \quad 0 \text{ otherwise} \end{cases}$$

A_i is the setup cost to construct platform i.

Decision variables for this model are as follows:

X is a matrix with binary entries describing components included in the platforms, such that:

$$x_{ij} = \begin{cases} 1 \text{ if platform } i \text{ contains component } j \\ \quad 0 \text{ otherwise} \end{cases}$$

Y is a binary matrix that states that product k is made on platform I, with elements:

$$y_{ki} = \begin{cases} 1 \text{ if the product } k \text{ is made using platform } i \\ \quad 0 \text{ otherwise} \end{cases}$$

The following variables are also used:

$$a_{ijk} = \begin{cases} 1 \text{ if the } j^{th} \text{ component is added manually to platform } i \text{ to form product } k \\ \qquad 0 \text{ otherwise} \end{cases}$$

$$r_{ijk} = \begin{cases} 1 \text{ if the } j^{th} \text{ component is removed manually from platform } i \text{ to form product } k \\ \qquad 0 \text{ otherwise} \end{cases}$$

6.3.1 The Single Platform Design Formulation

Minimize

$$\left(\sum_{j=1}^{|J|}\sum_{k=1}^{|K|}\left(CP_j + C_j\right)D_K X_{1j}\right) + \left(\sum_{j=1}^{|J|}\sum_{k=1}^{|K|}\left(CA_j + C_j\right)D_K a_{1jk}\right) + \left(\sum_{j=1}^{|J|}\sum_{k=1}^{|K|}\left(CR_j - C_j\right)D_k r_{1jk}\right) \quad (6.1)$$

Subject to:

$$a_{1j,k} = (1 - X_{1J})v_{j,k} \qquad \forall j,k \quad (6.2)$$

$$r_{1,j,k} \le (1 - v_{j,k})X_{1j} \qquad \forall j,k \quad (6.3)$$

$$X_{1j}, a_{1,j,k}, r_{1,j,k} = \{0,1\} \quad (6.4)$$

The objective (6.1) is to minimize the total production cost, which includes the cost of mass assembly (cost of producing platforms) and the cost of the components (I), the cost of manually adding components to the platform to produce the products (II), and the cost of removing components from the platforms (III) (with allowance to reuse the components). The constraint in (6.2) ensures that a component is added to the platform only if it is required in the product and not present in the platform. The constraint in (6.3) ensures that a component may be removed from the platform only if it is in the platform and it is not required in the product.

6.3.2 The Multiple Platform Problem

Minimize

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K}(CP_j + C_j)\cdot x_{ij}\cdot y_{ik}\cdot D_k + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}(CA_j + C_j)\cdot a_{ijk}\cdot y_{ik}\cdot D_k + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}(CR_j - C_j)\cdot r_{ijk}\cdot y_{ik}\cdot D_k + \sum_{i\in I} A_i \quad (6.5)$$

Subject to:

$$a_{ijk} = (1 - x_{ij}) \cdot v_{jk} \cdot y_{ki} \qquad \forall i \in I; j \in J; k \in K \qquad (6.6)$$

$$r_{ijk} \leq (1 - v_{jk}) \cdot x_{ij} \cdot y_{ki} \qquad \forall i \in I; j \in I; k \cup K \qquad (6.7)$$

$$\sum_{i=1}^{|I|} y_{ki} = 1 \qquad \forall k \in K \qquad (6.8)$$

$$x_{ij} \geq f_{jlk} y_{ki} x_{il} \qquad \forall i \in I; j, l \in J; k \in K \qquad (6.9)$$

$$I \in \{1, 2, \ldots, K\} \qquad (6.10)$$

$$x_{ij} \in \{0,1\}; y_{ki} \in \{0,1\}; a_{ijk} \in \{0,1\}; r_{ijk} \in \{0,1\} \qquad (6.11)$$

The objective (6.5) minimizes the cost, which includes the setup cost for each platform, the optimal set of components to include in each platform, and the optimal assignment of products to platforms. The first term in the objective function represents the cost of production via platforms. The second term represents the cost of adding components manually to the various platforms to form different products. The third term represents the cost of manually removing (and allowing reutilization) excessive components from the platforms to form each product. The last term represents the setup cost of constructing the platforms.

The constraint in (6.6) restricts component *j* to be added to platform *i* to make product *k* only if the component is not already in that platform; thus, component *j* is required for product *k*, and product *k* is assigned to platform *i*. The constraint in (6.7) states that component *j* may be removed from platform *i* if that component is not required in product *k*; thus, the component is assigned to platform *i* and product *k* is built from that platform. The constraint in (6.8) ensures that each product is made from only one platform. The constraint in (6.9) checks the assembly feasibility of each product that uses a platform so that if component *l* precedes component *j* in a product *k* assigned to the platform, and component *l* is assigned to the platform, then component *j* must be in the platform. The constraint in (6.10) states that the optimal number of platforms is an integer, and that the maximum number of platforms is limited by the total number of the products in the family. Finally, the constraint in (6.11) ensures binary decision variables.

6.3.2.1 Improving the Formulation

In the formulation in Section 6.3.2, constraints in (6.6), (6.7), and (6.9) are nonlinear, which makes selecting a solution procedure difficult, at best. The following changes are made to those constraints in order to attain a linear formulation.

Subject to:

$$a_{ijk} + x_{ij} \leq 1 \qquad \forall i \in I; j \in J; k \in K \tag{6.12}$$

$$a_{ijk} + x_{ij} \geq v_{jk} \qquad \forall i \in I; j \in J; k \in K \tag{6.13}$$

$$v_{jk} \geq a_{ijk} \qquad \forall i \in I; j \in J; k \in K \tag{6.14}$$

$$x_{ij} \geq r_{ijk} \qquad \forall i \in I; j \in J; k \in K \tag{6.15}$$

$$r_{ijk} + x_{ij} + v_{jk} \leq 2 \qquad \forall i \in I; j \in J; k \in K \tag{6.16}$$

$$1 + x_{ij} \geq f_{jlk} \cdot y_{ik} + x_{il} \qquad \forall i \in I; j, l \in J; k \in K \tag{6.17}$$

(6.12)–(6.14) replace the nonlinear constraint in (6.6), (6.15)–(6.16) replace the nonlinear constraint in (6.7); (6.17) replaces the nonlinear constraint in (6.9). The solution space is extremely large, with the total number of possible platform configurations being equal to $2^{|J||I|}$.

To reduce the solution space we introduce some cutting planes. The first cut was added to avoid the symmetrical nature of the problem; *i.e.*, the same solution can be represented in $|I|$! different ways by merely permuting the platforms. To eliminate such symmetry the following cut has been developed: $\sum_j x_{ij} \geq \sum_j x_{sj} \forall i, s \in I$. A similar cut used is: $\sum_k y_{ik} \geq \sum_k y_{sk} \forall i, s \in I$.

An additional cut that prevents the same component from being added and removed from the same platform is: $a_{ijk} + r_{ijk} \leq 1, \forall i \in I; j \in J; k \in K$.

The cuts above are included in the formulation and the model is solved. Adding the first cut reduces the computational time by more than 50%, while the next two cuts have a smaller contribution.

6.3.3 Single Platform Design under Stochastic Demand Problem

Assume that the platform supports *N* types of products. The facility mass-produces *w* units of a single type of platform. The manufacturer experiences stochastic demand for each of the products. If the actual total demand of all product types is higher than the inventory level of the mass produced platforms, sales are lost. On the other hand if the actual total demand of the product is less than the platform's inventory level, demands are satisfied and some holding (or inventory) cost is incurred for the unused platforms.

This problem can be formulated as a two stage stochastic programming model with recourse. The demand for each product is modeled as a set of demand scenarios, each with some probability of occurrence. The probabilities can be assessed during the product customization phase while interacting with the customer. The first stage decision variables are:

1. the configuration (components set of a platform);
2. the number of platforms (inventory level) to be produced.

The second stage decision variables are:

1. The additional components that would be added manually (*i.e.*, without using the mass production methods) to the platform to make a particular product type.
2. The components that would be manually removed from the platform to make a particular product type.
3. The quantity of each product type to be produced for each scenario.

The objective is to minimize the total production cost that includes the platform production cost, the cost of producing the products using the platforms, the holding cost of unused platforms and stock-out cost of lost demands, in addition to the cost of manually adding and removing components.

6.3.3.1 Model Formulation

The following additional notations are used to formulate the stochastic integer program:

1. $k = 1, 2, \ldots, |K|$ index of products
2. $j, l = 1, 2, \ldots, |J|$ index of components
3. $s = 1, 2, \ldots, S$ index of demand scenarios
4. h = platform holding cost, *per* unit
5. q_k = *per* unit stock-out cost for product k
6. ξ_s = vector of demands $(\xi_{1s}, \xi_{ss}, \ldots, \xi_{Ns})$ in scenario s
7. p_s = probability of occurrence of scenario s
8. $f_{jl} = \begin{cases} 1 \text{ if component } j \text{ precedes component } l \text{ according to the part} \\ \qquad\qquad \text{assembly relationship matrix} \\ \qquad\qquad 0 \text{ otherwise} \end{cases}$

Decision variables:

$$x_j = \begin{cases} 1 \text{ if the component } j \text{ participates in the platform} \\ \qquad 0 \text{ otherwise} \end{cases}$$

w = number of platforms to be produced

y_{ks} = units of product k to be produced using platforms in scenario s

$$a_{jk} = \begin{cases} 1 \text{ if the component } j \text{ is added manually to the platform to make product } k \\ \qquad 0 \text{ otherwise} \end{cases}$$

$$r_{jk} = \begin{cases} 1 \text{ if the component } j \text{ is removed manually} \\ \quad \text{from the platform to make product } k \\ \qquad 0 \text{ otherwise} \end{cases}$$

u_{ks}^{-} = lost demand of product k in scenario s

v_s^{+} = unused inventory of platforms in scenario s

The following model provides an optimal solution:
minimize

$$
\begin{gathered}
w\sum_{j=1}^{|J|}(CP_j + C_j)\cdot x_j + \\
\sum_{s=1}^{S} p_s \left(\sum_{k=1}^{|K|}\sum_{j=1}^{|J|}(CA_j + C_j)\cdot a_{jk}\cdot y_{ks} + \sum_{k=1}^{|K|}\sum_{j=1}^{|J|}(CR_j - C_j)\cdot r_{jk}\cdot y_{ks} \right) + \\
\sum_{s=1}^{S} p_s \sum_{k=1}^{|K|} q_k u_{ks}^{-} + \sum_{s=1}^{S} p_s \cdot h \cdot v_s^{+}
\end{gathered}
\tag{6.18}
$$

Subject to:

$$a_{jk} + x_j \le 1 \qquad \forall j \in \{1,2,\ldots,|J|\}, k \in \{1,2,\ldots,|K|\} \tag{6.19}$$

$$a_{jk} + x_j \ge v_{jk} \qquad \forall j \in \{1,2,\ldots,|J|\}, k \in \{1,2,\ldots,|K|\} \tag{6.20}$$

$$v_{jk} \ge a_{jk} \qquad \forall j \in \{1,2,\ldots,|J|\}, k \in \{1,2,\ldots,|K|\} \tag{6.21}$$

$$x_j \ge r_{jk} \qquad \forall j \in \{1,2,\ldots,|J|\}, k \in \{1,2,\ldots,|K|\} \tag{6.22}$$

$$r_{jk} + x_j + v_{jk} \le 2 \qquad \forall j \in \{1,2,\ldots,|J|\}, k \in \{1,2,\ldots,|K|\} \tag{6.23}$$

$$w - v_s^{+} = \sum_{k=1}^{|K|} y_{ks} \qquad \forall s \in \{1,2,\ldots,S\} \tag{6.24}$$

$$y_{ks} + u_{ks}^{-} = \xi_{ks} \qquad \forall s \in \{1,2,\ldots,S\}, k \in \{1,2,\ldots,|K|\} \tag{6.25}$$

$$1 + x_j \ge f_{jl} + x_l \qquad \forall j,l \in \{1,2,\ldots,|J|\} \tag{6.26}$$

$$x_j \in \{0,1\}; a_{jk} \in \{0,1\}; r_{jk} \in \{0,1\}; y_{ks} \ge 0; w \ge 0; u_{ks}^{-} \ge 0; v_s^{+} \ge 0 \tag{6.27}$$

The objective function in (6.18) represents the total production cost and includes the cost of producing the platforms, assembling the products using the platforms, the total stock-out costs, and the total holding cost under all possible scenarios. Constraints in (6.19)–(6.21) state that component *j* must be added to the platform to make product *k* if *j* is not already in the platform (and is required in product *k*). Constraints in (6.22) and (6.23) state that component *j* may be removed from the platform to make product *k* if that component is in the platform and is not required in product *k*. The constraint in (6.24) shows that for any scenario, the total number of products produced cannot exceed the total number of platform in inventory. The constraint in (6.25) limits the total number of units produced of product *k* to be equal to the random demand value of product *k* for any scenario plus the lost demand. The constraint in (6.26) checks the assembly feasibility of the platform while deciding its configuration. This constraint states that if component *l* is in the platform and, according to the part assembly relationship, component *j* precedes *l* ($f_{jl} = 1$), then *j* must also be present in the platform. The constraint in (6.27) ensures the binary and non-negativity nature of the decision variables.

6.4 An Illustrative Example

In this section a small hypothetical example is used to illustrate the solution to the problem presented in Section 6.3.3. The stochastic model is validated by calculating the *stochastic solutions*, *expected value solutions*, and *solutions in case of perfect information*. The model is validated by showing that the *value of stochastic solutions*, VSS (*expected value solution – stochastic solution*) and *expected value of perfect information*, EVPI (*stochastic solution – solution in case of perfect information*) are positive for various instances of the example.

Stochastic solutions are determined by solving the stochastic integer program presented in Section 6.3.3. Expected value solutions are determined by making the value of w (number of platforms to be mass produced) equal to the sum of the expected demand of all products and solving the stochastic integer program with this fixed value of w. The solution in case of perfect information is determined by solving the model by taking one scenario at a time with a given demand value for that scenario; the cost value is then determined for that scenario. Finally the weighted sum of the costs for all scenarios is calculated, where the weight of a scenario is given by the scenario's probability, and that is considered to be the cost in the case of perfect information.

The example uses a family of three products (P1, P2, and P3). The binary bills of materials of the products and the PAR matrix are shown in Tables 6.2 and 6.3, respectively.

Data common for all the scenarios are presented below. There are four distinct components with costs as shown in Table 6.4.

Table 6.2 Material participation matrix (v_{jk}) for the three products

	A	B	C	D
P1	1	1	0	1
P2	1	1	1	0
P3	1	1	0	0

Table 6.3 The product family PAR (f_{jl}) matrix

	A	B	C	D
A		1	1	
B				1
C				
D				

Table 6.4 Various cost used in the example

Component	A	B	C	D
Purchasing cost (US $)	10	11	12	13
Assembly cost (US $)	2	2	2	2
Adding cost (US $)	4	4	4	4
Removal cost (US $)	2	2	2	2

This small example is solved exactly using OPL 3.5 (from ILOG Corporation). The reason for taking such a small size problem was that OPL 3.5 took over 40 h to solve it. That prompted us to develop heuristic based approaches for large, real life problems (see, *e.g.*, Ben-Arieh and Choubey 2008).

Table 6.5 provides the solutions for different demand scenarios, shortage and holding costs, and probabilities of scenario occurrences. Based on the data provided in Table 6.5, the following observations are made:

1. The positive values of VSS and EVPI provide evidence of model correctness; it is obvious that there is an advantage in using the stochastic model over expected solution approaches.
2. When the probability of occurrence of a particular scenario is high, the solutions tend to shift towards that scenario (Cases 1, 2, 3, and 5) except for the case of expected value solutions. For a very symmetric case (Case 4) all three types of solutions are the same, which means that for near symmetric cases using the expected value solution approach would work well.

Table 6.6 provides a sensitivity analysis of the holding cost and shortage cost using various cases. Based on the data presented in Table 6.6, the following can be concluded:

1. When the total demand of products is similar over various scenarios the number of products to be made in each scenario depends solely on the products' shortage costs (Case 1). In addition, the shortage cost should be sufficiently high to justify the production of products as we have not considered the profit obtained by producing items in our model (see Case 2).
2. When there is high variability in total demand over different scenarios, the increase in holding costs encourages lower production for given shortage costs (see Cases 1 and 2).

Figure 6.3 shows the effect of variance in demand and the number of scenarios considered in the stochastic model on the stochastic solution. This figure is a plot of total production cost *vs.* number of demand points considered in the demand distribution for each product *vs.* the standard deviation in a normally distributed demand. The mean demand for each product is kept fixed at 100 units. The figure clearly illustrates that increasing the number of demand points considered in the probability distribution (creating more scenarios) causes the stochastic cost value to decrease; similarly increasing the normal standard deviation leads to an increase in the cost value. These instances of the example are solved using a genetic algorithm approach.

Figure 6.4 shows the advantage of the stochastic model over other models. Figure 6.4 is a plot of objective (cost) value *vs.* standard deviation obtained by using the stochastic model, the expected solution model, and the case of perfect information for the example. All products have the same mean values for their demand distribution and standard deviation is increased for all products. The models are solved using a genetic algorithm method.

Table 6.5 Various solutions for the different instances of the example

Case 1 h = US $5		q_1 $200	q_2 US $100	q_3 US $100	*Expected value sol.* Obj. val. = 9086 w = 240			*Stochastic sol.* Obj. val. = 8790 w = 250			*Perfect information* Obj. val. = 8490 $w1$ = 250; $w2$ = 200			VSS	EVPI
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	US $296	US $300
S1	0.8	100	50	100	100	50	90	100	50	100	100	50	100		
S2	0.2	50	100	50	50	100	50	50	100	50	50	100	50		
Case 2 h = US $5		q_1 US $200	q_2 US $100	q_3 US $1	Obj. val. = 6606 w = 240			Obj. val. = 6330 w = 150			Obj. val. = 6014 $w1$ = 200; $w2$ = 200			US $276	US $316
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3		
S1	0.8	100	50	100	100	50	90	100	50	0	100	50	100		
S2	0.2	50	100	50	50	100	50	50	100	0	50	100	50		
Case 3 h = US $50		q_1 US $100	q_2 US $100	q_3 US $100	Obj. val. = 12840 w = 220			Obj. val. = 10365 w = 200			Obj. val. = 7595 $w1$ = 500; $w2$ = 200			US $2475	US $2770
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3		
S1	0.1	200	200	100	150	70	0	0	100	100	200	200	100		
S2	0.9	50	100	50	50	100	50	50	100	50	50	100	100		
Case 4 h = US $50/80/100		q_1 US $100	q_2 US $100	q_3 US $100	Obj. val. = 8725 w = 250			Obj. val. = 8725 w = 250			Obj. val. = 8725 $w1$ = 250; $w2$ = 250			US $0	US $0
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3		
S1	0.5	100	50	100	100	50	100	100	50	100	100	50	100		
S2	0.5	50	100	100	50	100	100	50	100	100	50	100	100		
Case 5 h = US $5		q_1 US $100	q_2 US $100	q_3 US $100	Obj. val. = 20368 w = 470			Obj. val. = 18835 w = 500			Obj. val. = 16265 $w1$ = 500; $w2$ = 200			US $1533	US $2570
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3	Y_1	Y_2	Y_3		
S1	0.9	200	200	100	200	170	100	200	200	100	200	200	100		
S2	0.1	50	100	50	50	100	50	50	100	50	50	100	50		

Table 6.6 Sensitivity analysis on holding costs and shortage costs

Case # 1 h = US $50/80/100		q_1 US \$100	q_2 US \$100	q_3 US \$100	*Stochastic sol.* Obj. val. = US \$8790 $w = 250$		
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3
S1	0.8	100	50	100	100	50	100
S2	0.2	50	100	50	50	100	50
Case # 2 h = US \$50/80/100		q_1 US \$20	q_2 US \$20	q_3 US \$20	Obj. val. = 5000 $w = 0$		
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3
S1	0.5	100	50	100	0	0	0
S2	0.5	50	100	50	0	0	0
Case # 3 h = US \$50		q_1 US \$102	q_2 US \$101	q_3 US \$100	Obj. val. = 18825 $w = 320$		
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3
S1	0.5	200	100	100	200	100	20
S2	0.5	100	50	50	100	50	50
Case # 4 h = US \$100		q_1 US \$102	q_2 US \$101	q_3 US \$100	Obj. val. = 27830 $w = 200$		
Scenarios	Pr.	ξ1	ξ2	ξ3	Y_1	Y_2	Y_3
S1	0.5	200	100	100	200	0	0
S2	0.5	100	50	50	100	50	50

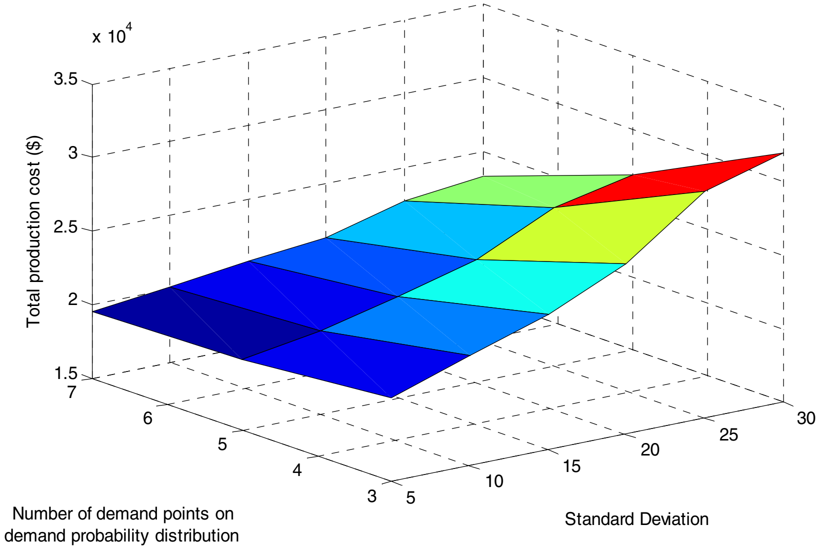

Figure 6.3 Effect of demand variance and the number of scenarios considered in the stochastic model on the stochastic solution

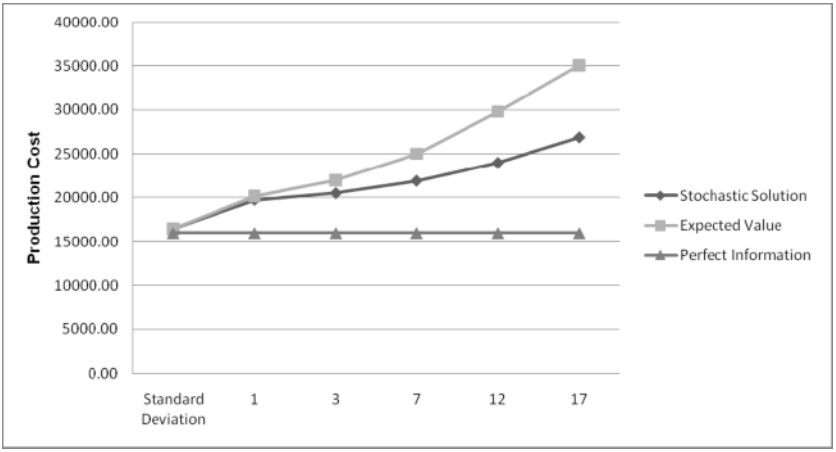

Figure 6.4 Various cost values when increasing the standard deviation of the demand distribution

Based on Figure 6.4 it is possible to conclude that the expected value model is recommended in cases where variance in demand is not very high; otherwise, the stochastic model should be used.

6.5 Conclusion and Recommendations for Future Research

This chapter proposes a platform based optimization approach for the economic production of a product family under different production strategies; namely, using a single or multiple platforms, and considering demand uncertainty.

In the case of stochastic demand the chapter establishes the adequacy of the stochastic model for the platform based production approach, especially when variance in demand is high. The effects of demand variance and various cost components on the optimal platform strategy have also been discussed. The platform based production approach is also explained and illustrated with an example.

Only a very small instance of the problem could be solved by exact approach using OPL 3.5. Therefore, we recommend using heuristic methods that can provide good solutions to large instances of the problem more quickly. One such approach that combines a genetic search process with integer programming provides a near optimal solution for large instances of the problem in reasonable time; yet this approach takes a long time to solve problems with a large number of demand scenarios. Another method – a pure probability based genetic search heuristic – solves problems with a large number of demand scenarios very quickly but with slightly inferior solution quality than the first heuristic approach.

Future work in this area includes consideration of more complex cost structures, and multi-period demand settings with some inventory management policy such as base stock policy. The correlation in demands of the products can be used to capture *cannibalization* effects or to make the problem more tractable for optimization by reducing the number of independent demand scenarios.

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Chapter 7
Shape Commonalization to Develop Common Platforms for Mass Customization

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Abstract To be a global leader in the current market, a company needs to keep on adapting to the changing requirements of its customers and also provide customization of its products to suit the customers' needs. A robust *product platform* can support a variety of products to satisfy different segments of the market with reduced manufacturing and product development cost. The common components for a set of similar products belonging to a family can be grouped into a common platform. However, development of product platform requires measuring similarity among a set of products. This chapter presents an approach to measure the *degree of similarity* among a set of products by extracting the information from their existing CAD models. The extraction process leads to a suitable development of *shape commonality indices* to identify the components and products that can be potentially arranged under a common platform. Two case studies are presented to demonstrate the steps of the approach.

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Abbreviations

CAD	Computer-aided design
MLD	Multiple levels of details
AAPCI	Average assembly platform commonality index
AC	Average commonality for a feature-set
ACPCI	Average component platform commonality index
API	Application programming interface
BBB	Basic building block
DC	Dimensional commonality
IGES	Initial graphics exchange specification
LRE	Lower reservoir extrusion
NOC	Number of component-sets in a given product-set
NOF	Number of feature-sets in a given component-set
PC	Positional commonality
S	Shell
STEP	Standard for the exchange of product model data
UOC	Upper opening cut
UoS	Union of spheres
WPC	Warming plate cut
WPE	Warming plate extrusion

7.1 Introduction and Background

The current market place is characterized by customers with a diverse set of requirements, with customers changing their demands frequently. In order to compete in the current global market, companies are now determined to treat customers as individuals with different needs rather than lump them into homogeneous groups. A well defined product platform is necessary to support *mass customization* or provide varieties.

With the development of technology, the use of *CAD in design* has increased significantly in recent decades. In such a design environment, establishing a common platform for a set of similar products or mass customization will require measuring the *commonality* among similar components used in a range of products. A technique to measure the similarity among the different 3D models would enable faster development of the product platform. Consequently, one of the challenges that need to be addressed for more efficient and effective use of 3D CAD to support mass customization and develop efficient product platforms will be to compare and identify 3D CAD models of components and products that are common or similar.

Existing *shape matching techniques* apply a *two stage* process, first transforming the shape and then measuring the resemblance with using similarity measures. During shape matching processes, the applied *transformations* often ignore the attributes of the CAD models, which have significant design information. However, there is a lack of research on measuring the *geometric* (*shape*) *commonality* of components, especially for 3D solid models. The shape commonality between a set of components could be used as a key factor in designing product platforms from an existing set of components, optimizing existing product platforms to increase component commonality, and searching component databases to identify similar components. Thus, it is becoming necessary for product designers to measure the shape commonality between a given set of components. This chapter addresses the following research question: how can we compare and measure *commonality of 3D CAD models* of products to develop common platforms?

7.2 Literature Review

7.2.1 Product Platform

There has been substantial research conducted in the areas of product family design. Duray and Milligan (1999) discussed the significance and effects of involving customers at various stages in the product development and manufacturing process. The authors present *common characteristics and practices* of mass customizers. Simpson *et al.* (2005) described two basic approaches to product family design – "*top-down*" (proactive platform) approach and "*bottom-up*" (reactive design) approach. In the top-down approach, the product family is derived, developed, and managed from a product platform. In the bottom-up approach, a group of distinct products are redesigned and standardized in order to improve economies of scale.

Shooter (2005) has described the top-down approach used by *Innovation Factory* in the development of the "IceDozer" product family of ice scrapers using the platform concept. The *top-down* approach used resulted in an increase in product variety in the existing product line, lower tooling costs, and shorter lead times for development. This was largely due to the use of standardized components, which made it easier to develop additional variants in the product line by simply introducing extensions to the existing products. The success achieved by Innovation Factory proved that product family concept is beneficial not only to large firms but also to small start-up firms.

Halman *et al.* (2003) investigated why companies are adopting product family and platform concepts, along with the methodologies used to develop, implement, sustain, and monitor these concepts. In the paper the authors concluded that even though the products offered by the companies differed substantially, all the companies under investigation used the product family concept for the same goals, anticipated *similar risks*, and expected *similar benefits*.

Fellini *et al.* (2003) presented a *strategy* to identify and select the product platform for a given product family, based on the individual optimization results of the variants in the family. Product variants in the family are obtained by incorporating the functions that they are required to perform. The *assumption* is that product variety in a product family can be achieved by making only *minor changes* in the design. The individual variant designs are used to formulate a metric, known as the performance deviation vector. Based on the values in the vector, commonality decisions are made and the product family is *optimized* and designed around the chosen platform. This technique is applied to redesign a product family of automotive body structures.

Alizon *et al.* (2008) discussed two development strategies to derive product families: (1) *a platform-driven strategy* and (2) *a product driven strategy*. In a platform-driven process, the platform is specified at the beginning and all the products in the family are developed and launched at the same time based on this platform. In the product-driven process, only one product goes through the process from design to manufacturing and is then launched in the market. So, the platform is not directly specified and the initial product is used as the basis for future variants.

Khire *et al.* (2008) presented a *product family commonality* selection method based on individual product optimization and interactive visualization by the designer. Sandborn *et al.* (2008) applied the product platform design concepts to determine the best *reuse* of the electronic components. The authors concluded that timing and supply chain disruptions should be taken into account in designing product platform. Alizon *et al.* (2008) proposed two novel *indices* emphasizing shape and functional similarity to achieve differentiation within a family of products.

It can be concluded from the literature summarized in this section that product platform development is a *multivariable problem*. Various similarity issues such as functions, costs, shape, manufacturing process, *etc*., should be considered for the successful development of product platforms. In order to support product platform development, especially for an existing set of components, measuring the *geometric similarity* is one of the challenging tasks that need to be performed. In this research, an approach to develop a *common platform* based on shape similarity for an existing set of products derived from their CAD models is presented. This approach can be used in parallel with the other available platform development techniques and can be extended taking other issues into account in the future.

7.2.2 Similarity Measurements

Many researchers have focused their attention on the problem of representing 3D models in a format useful for measuring similarity. Shen *et al.* (2003) proposed a *shape descriptor* based on 2D views (images rendered from uniformly sampled positions on the viewing spheres), called *light field descriptor*, to represent a 3D model useful for similarity measurement. Since it is based on *2D images*, it is unable to represent the internal features, which are important design information contained in CAD models.

Lu *et al.* (2007) proposed a *partial geometric feature* based approach, which is based on curve-skeleton histogram. Here, a curve skeleton is extracted from 3D models using the electrostatic field function. Extracted curves are divided into a number of segments based on electrostatic concentration. A thickness distribution histogram is generated from all segments of the curve skeleton that are grouped based on topological and curvature information. The histogram is used for similarity measurement. Since CAD models are modified during the process of measuring similarity, it is not possible to keep track of features which are dissimilar. The modification process often ignores some of the features which might be important to represent 3D CAD models.

Cornea *et al.* (2005) used a *curve skeleton* of a 3D object, which is capable of capturing the essential topology of an object in three dimensions for similarity measurement. It has the additional advantage of measuring the similarity of parts/components from an *assembly*.

Pu *et al.* (2006) proposed an MLD (*multiple levels of detailed*) representation of 3D CAD models. The approach uses three orthogonal views (front view, side view, and top view) to represent a 3D model. They extend their orthogonal view based 3D similarity approach by splitting the information into three distinct levels of detail (silhouette, contour, and drawing level).

McWherter and Regli (2001) presented an approach for *indexing* solid models of mechanical components from boundary representations and engineering attributes, which are mapped into graphs known as "*model signature graphs*"; the graphs are projected into multi-dimensional metric spaces called "*model comparison spaces*". Three distance matrices are computed between the CAD models using vector spaces. Sharf *et al.* (2004) combined topology, geometry, feature characteristics, and positioning of 3D objects by approximating their volume using a UoS (*union of spheres*) representation. Spagnuolo *et al.* (2006) proposed *structural descriptors* to represent 3D objects based on differential topology. Akgül *et al.* (2007) used *density based shape descriptors* using kernel densities derived from the probability density functions of local surface features characterizing the 3D object geometry. The 3D object is represented by a collection of triangular mesh. The information of the entire triangular area is exploited using an integration scheme. By using the intermediate kernel, the local geometric information from the triangular mesh is accumulated to density points resulting in a global shape description.

Lele and Richtsmeier (1991) proposed a new method for comparing *biological shapes* based on the *Euclidean distance matrix* representation of the form of an object. Siegel and Benson (1982) used *resistant fitting* techniques to determine localized differences in the form of two related animal skeletons.

All the works presented in this section describe various approaches to transform 3D shapes for similarity measure, with focus on 3D graphical models (models used in medical imaging, movie industry, *etc.*), rather than CAD models, which have directed the research in *global shape matching*. When comparing 3D CAD models designers often want to identify and modify the features, which are dissimilar. Using global shape matching, identification of similar shapes/features is not allowed, which is the *first step* towards modifying 3D component geometry to increase commonality.

7.3 Method

The key challenge in measuring similarity is to represent CAD models of components to facilitate the identification of common geometrical shapes/features. As indicated in the Literature Review, researchers have proposed various approaches to turn a 3D shape usable for similarity measurement, focusing on 3D graphical models rather than CAD models. In CAD design shapes often have high genus and contain important features of various types. These can include holes, ribs, fillets, shells, *etc*. Their numbers, as well as relative positions are important factors when measuring similarities.

With the development of technology, the use of CAD in design has become commonplace. A relative advantage of 3D CAD models over other 3D graphics is that CAD models have to be created by using certain features and then specifying the dimensions. It is possible to retrieve the features used in a CAD model and the relative dimensions of the sketches drawn under the features.

The approach presented in this chapter identifies common platforms by extracting the geometric information directly from CAD models. The extracted features and parametric information are then used to determine the components' commonality. The proposed process also highlights commonality of features for components being compared, which facilitates increasing the commonality of platforms.

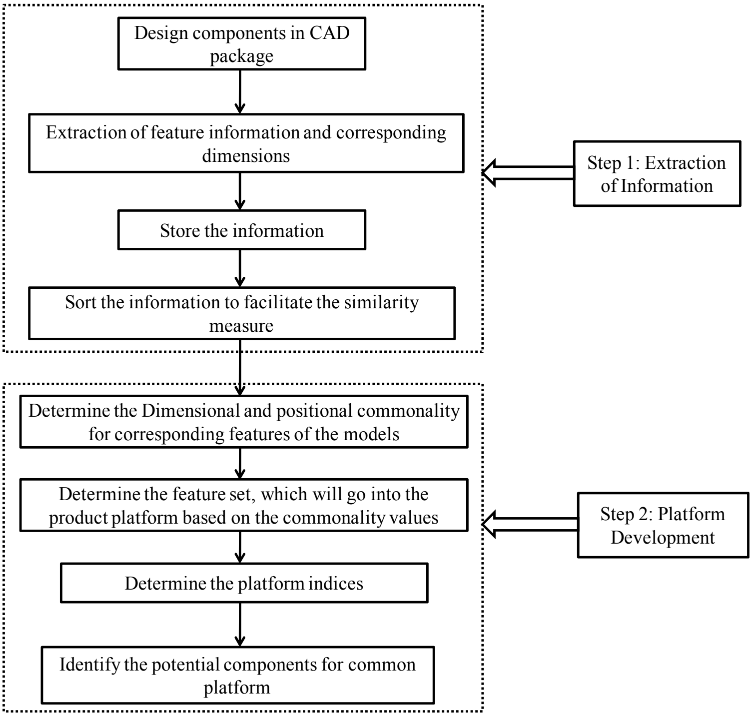


Figure 7.1 The overall approach to measure the common platform

Since there is no transformation of original models involved in the approach, all significant attributes of a model will be considered.

The overall process for identifying similarity among 3D CAD models can be divided into two steps (Figure 7.1):

Step 1: extraction of information from 3D models;
Step 2: common Platform development.

Detailed activities for the two steps are presented next.

7.3.1 Step 1: Extraction of Information from 3D Models

In Step 1, all the important information of the CAD model is extracted and stored in a sequential order to make the comparison process easier and correct. The information of the model is extracted using the CAD software capability to keep track of all information that is given as input during the development, as long as it remains on the same CAD platform. However, the exchange of models among different CAD systems through several neutral formats (such as IGES, STEP, *etc.*) no longer ensures the availability of parametric information. Information can only be extracted from the original model, which did not undergo any exchange among CAD systems. Activities related to Step 1 are described in this section.

7.3.1.1 Design Components in CAD

The process starts by designing the components in the CAD environment. Any CAD software available in the market can be used. In this research, SolidWorks was used to develop the CAD models. SolidWorks has built in applications and functions to facilitate automated extraction of feature and geometric information. In this research it is assumed that the designer will be consistent in the process of creating the 3D CAD models. To facilitate the development of consistent models, the following rules are proposed:

1. The designers will follow the same sequence to build the model regardless of what planes are being used to start the design.
2. The positional dimensions of a feature will be determined after the physical dimension (feature parameters).
3. The positional dimensions will be placed from the same reference for each model.
4. It is assumed that the designer will specify every dimension clearly.

7.3.1.2 Extraction of Feature Information and Corresponding Dimensions

During the development of the CAD model, the designer specifies all *feature information and dimensions* as input to the CAD software. The CAD software manages all information specified by the designer and creates the model accordingly. Model information, representing the CAD model, is extracted from the CAD software to compare different models. SolidWorks has a *feature manager design tree*, where all model information is stored sequentially. SolidWorks API (*application programming interface*) contains functions, routines, protocols, and tools to link with the feature manager design tree. Macros can be developed to extract the information of the models from the feature manager design tree.

In SolidWorks *macro programming* is also very strong. By writing appropriate macros using the API functions all the information from the feature manager design tree may be collected. Macro programming has another advantage: one single macro is sufficient to extract all the information from different models; there is no need to develop specific macros for different models. SolidWorks macros are written in Visual Basic. The challenge here is to determine how efficiently the API functions can be used through macro programming such that all the necessary information can be extracted from the model.

7.3.1.3 Storing and Sorting the Information

The extracted information is *stored* in a *text file*. After information storage, CAD models are not required to compare the models from the next step. The information needs to be sorted before storing, so that comparison can be easily automated. Every designer has his/her own *vision and style* in creating CAD models. A model can be created in different ways in terms of selecting the features and placing dimensions. Different designers, or even the same designer at different times, perform these tasks differently. As a result the same model may be represented by different file contents. The challenge is to organize the contents in such a way that the files can be recognized as representing the same model. An algorithm has been developed and implemented as a macro to load the information in a certain order and not in the way they are organized in the feature manager design tree. Steps for sorting the information are the following:

1. For every model (and corresponding text files), traverse through the feature information.
2. For every feature, traverse through the sketch information.
3. For every sketch, traverse through the dimension information.
4. Separate the positional dimensions [last two dimensions (x,y)] and physical dimensions (rest of the dimensions).
5. For the positional dimensions, sort them with the increasing value of x or y. Sort the sketch information under the feature according to the sorted set of positional dimensions.

Follow Steps from 1 to 5 for the rest of the models.

7.3.2 Step 2: Common Platform Development

In Step 2, different models developed using *SolidWorks CAD system* are compared to calculate commonality indices using the information extracted in Step 1. The commonality indices are then used to develop common platforms for products. Activities in Step 2 focus on the comparison of models to identify features (in a set of components) and components (in a set of assemblies) that are (1) common and (2) similar but with potential to be common, for inclusion in the platform.

The sorted text files are used for similarity comparison. All feature information is rearranged sequentially for the models by going through the information contained in the files and identifying corresponding feature sets taken for comparison. The positional and physical dimensions (feature parameters) of the sketches under the feature set will be used to determine the positional and dimensional commonality indices for a feature set.

7.3.2.1 Indices for Component Shape Comparison

Shape commonality can be considered as the degree to which a given mechanical component is similar to another component from a purely *geometrical viewpoint*. In other words, it is the extent of commonality of their topological constructions. A common way to express the shape commonality among components is by using *commonality indices*. These indices express the commonality as a quantitative value, which makes it easier for designers to get a clear idea about the commonality of a component set.

In this research, to compare components and express the shape commonality quantitatively, commonality indices have been formulated. Components are compared *feature-wise* (a set of similar features at a time) in this study. The fundamental entity of any component is the basic building block (BBB). BBB is the main underlying shape upon which sub-features are constructed by performing geometrical operations. The shape commonality that exists among components is commonality of dimensions and positions of the BBB and the sub-features. Indices to compute the positional or dimensional commonality are presented next.

Dimensional Commonality Indices

Features are the fundamental entities of 3D CAD models in SolidWorks that contain all the required geometries and related parameters. Hence, components are compared feature wise in this study. When all features of a component in the feature-set are of the same type, the dimensional commonality measure for each feature-set is computed using (7.1):

$$(DC)_F = \frac{1}{t}(d_1 + d_2 + d_3 + \ldots\ldots + d_t) \tag{7.1}$$

where

$(DC)_F$ = dimensional commonality measure for any given feature-set;

n = number of component models to be compared feature wise;

$1, 2, 3, \ldots, t$ = various types of dimensions (length, width, height, depth, or radius) used to represent the feature;

t = total number of dimensions for the feature in question;

$d_{j1}, d_{j2}, d_{j3}, \ldots, d_{jn}$ = the dimensional values of type j in corresponding features;

d_{jm} = maximum dimension value of type j in the entire feature-set;

$deld_1, deld_2, \ldots, deldt$ = normalized difference among the dimensions for different types in the feature-set:

$$deld_1 = \frac{1}{(n-1)}\left(\frac{d_{1m}-d_{11}}{d_{1m}} + \frac{d_{1m}-d_{12}}{d_{1m}} + \frac{d_{1m}-d_{13}}{d_{1m}} + \ldots\ldots.. + \frac{d_{1m}-d_{1n}}{d_{1m}}\right)$$

$$deld_2 = \frac{1}{(n-1)}\left(\frac{d_{2m}-d_{21}}{d_{2m}} + \frac{d_{2m}-d_{22}}{d_{2m}} + \frac{d_{2m}-d_{23}}{d_{2m}} + \ldots\ldots + \frac{d_{2m}-d_{2n}}{d_{2m}}\right)$$

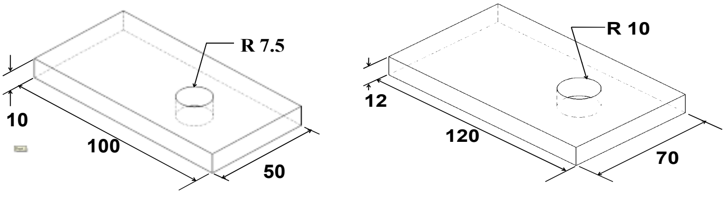
$$\ldots.. \quad \ldots.. \quad \ldots.. \quad \ldots.. \quad \ldots.. \quad \ldots\ldots$$

$$deld_t = \frac{1}{(n-1)}\left(\frac{d_{tm}-d_{t1}}{d_{tm}} + \frac{d_{tm}-d_{t2}}{d_{tm}} + \frac{d_{tm}-d_{t3}}{d_{tm}} + \ldots.. + \frac{d_{tm}-d_{tn}}{d_{tm}}\right)$$

$$d_1 = 1 - deld_1,\ d_2 = 1 - deld_2,\ d_3 = 1 - deld_3, \ldots.. d_t = 1 - deld_t .$$

If the features in a feature-set are not of the same type, *i.e.*, if both are not rectangular, the dimensional commonality measure for that feature-set is considered as zero.

Two simple blocks are shown in Figure 7.2. Each block has a through hole with different dimension and center position. The dimensions (radius, depth) of holes for the two blocks are (7.5, 10 mm) and (10 12 mm). The dimensional commonality of the hole-pair is calculated using equation (1). Parameters are: $n=2$ (two blocks are compared) and $t=2$ (number of dimensions). Radius (1) and depth (2) are the two dimensions for the hole-pair. The dimensional commonality calculations are shown in Table 7.1.



Model 1 Model 2

Figure 7.2 Physical dimensions (parameters) shown in the illustrative example

Table 7.1 Dimensional commonality calculation for the hole feature

Radius	Depth
d11 = 7.5; d12 = 10; d1m = 10	d21 = 10; d22 = 12; d2m = 12
$deld_1 = \frac{1}{(2-1)}\left(\frac{10-7.5}{10}+\frac{10-10}{10}\right)=\frac{1}{4}$	$deld_2 = \frac{1}{(2-1)}\left(\frac{12-10}{12}+\frac{12-12}{12}\right)=\frac{1}{6}$
$d_1 = 1-\frac{1}{4}=\frac{3}{4}$	$d_2 = 1-\frac{1}{6}=\frac{5}{6}$
$(DC)_H = \frac{1}{2}\left(\frac{3}{4}+\frac{5}{6}\right)=0.79$	

Positional Commonality Indices

When features in the feature-set are of the same type and they are on the same corresponding faces in the respective models, the positional commonality measure for the feature-set in the models is computed using (7.2):

$$(PC)_F = 1 - del \tag{7.2}$$

where:

$(PC)_F$ = positional commonality measure for any given feature-set in the models

CX_i, CY_i, CZ_i = x, y, and z coordinate of geometric center of the feature in model i

n = Number of component models to be compared feature wise.

CX_m, CY_m, CZ_m = the maximum dimension along the x, y, and z direction respectively

$delX$, $delY$, $delZ$ = normalized difference between the x, y, and z coordinates of the geometric centers of feature set

$$delX = \frac{1}{(n-1)}\left(\frac{CX_m - CX_1}{CX_m}+\frac{CX_m - CX_2}{CX_m}+\ldots..+\frac{CX_m - CX_n}{CX_m}\right)$$

$$delY = \frac{1}{(n-1)}\left(\frac{CY_m - CY_1}{CY_m}+\frac{CY_m - CY_2}{CY_m}+\ldots...+\frac{CY_m - CY_n}{CY_m}\right)$$

$$delZ = \frac{1}{(n-1)}\left(\frac{CZ_m - CZ_1}{CZ_m}+\frac{CZ_m - CZ_2}{CZ_m}+\ldots..+\frac{CZ_m - CZ_n}{CZ_m}\right)$$

del = Average normalized difference between the coordinates of geometric centers of feature-set.
$del = Avg(delX + delY + delZ)$

If the same type of feature is not on the same corresponding faces in each model, or when the same type of features are not present in each model, then $(PC)_F = 0$.

The rectangular blocks of Figure 7.2 are reused to calculate the positional commonality of the hole-pair using (7.2). The geometric center (Figure 7.3) of holes in the two blocks are (65,25,5) and (80,40,6). The positional commonality index calculation for the hole pair ($n = 2$) is shown in Table 7.2.

The feature in question may be the BBB of the components or a sub-feature. The comparison is performed only between corresponding features of the same type, for example, a circular hole in a model is compared only with a circular hole in other models, a rectangular pocket in a model is compared only with rectangular pockets in other models and the BBB of a model is compared with the those of other models. The type of dimensions differs depending on the type of features being compared. For a rectangular BBB, the dimensions to be compared are the length, width, and height; hence the total number of dimensions (t) is 3. For a circular hole, the dimensions to be compared are the radius and the depth of the hole and hence the total number of dimensions is 2. For any dimension, say the length of a rectangular pocket, the component that has a largest value of length is used to assign the value to "d_{1m}" [if the length is considered as the dimension type 1, hence $j = 1$ using (1)]. For example, if the length of the rectangular pocket in model 1 is 30 units and that in model 2 is 50 units, $d_{11} = 30$, $d_{12} = 50$ and $d_{1m} = 50$. The same rule is applied for all feature dimensions in the model. The total dimensional commonality measure DC for a feature-pair will be equal to 1 if each and every dimension in model 1 is equal in magnitude to the corresponding dimension in model 2.

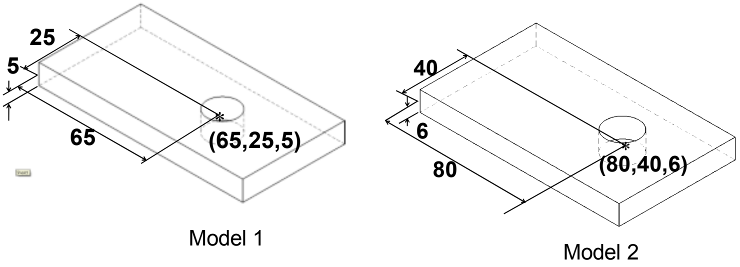


Figure 7.3 Positional dimensions shown in the illustrative example

Table 7.2 Positional commonality calculation for the hole feature

X	Y	Z
$CX_1 = 65$; $CX_2 = 80$; $CX_m = 80$	$CY_1 = 25$; $CY_2 = 40$; $CY_m = 40$	$CZ_1 = 5$; $CZ_2 = 6$; $CZ_m = 6$
$delX = \frac{1}{(2-1)}\left(\frac{80-50}{80} + \frac{80-80}{80}\right)$	$delY = \frac{1}{(2-1)}\left(\frac{40-25}{40} + \frac{40-40}{40}\right)$	$delZ = \frac{1}{(2-1)}\left(\frac{6-5}{6} + \frac{6-6}{6}\right)$
$= \frac{3}{8}$	$= \frac{15}{40}$	$= \frac{1}{6}$
$(del)_H = Avg(\frac{3}{8} + \frac{15}{40} + \frac{1}{6}) = 0.31$		
Positional commonality of the hole pair $(PC)_H = 1 - 0.31 = 0.69$		

Two coffeemaker lower housing component models are shown in Figure 7.4. Each of them possesses five features:

1. basic building block;
2. lower reservoir extrusion;
3. warming plate cut;
4. upper opening cut;
5. shell.

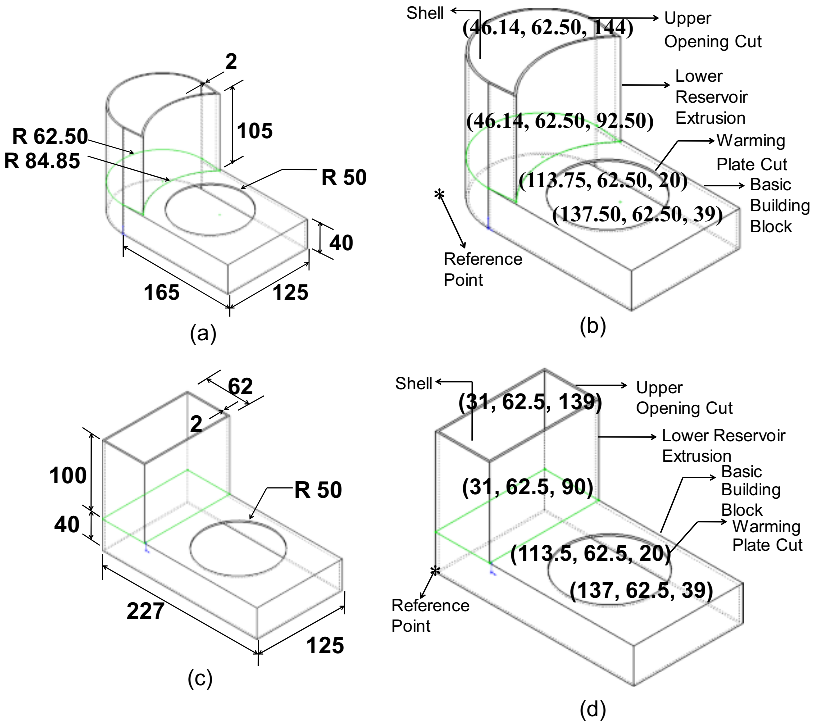


Figure 7.4 Two coffeemaker lower housing component models showing physical dimensions of lower housing 1 and 2 (a, c) and geometric center positions of the lower housing 1 and 2 (b, d)

The components are compared feature wise to calculate the dimensional and positional commonality between them using (7.1) and (7.2). Since the BBB, lower reservoir extrusion (LRE) and upper opening cut features of the two component models are not of the same type from the geometric point of view, the dimensional commonality of the feature-pairs are considered as 0. The dimensional and positional commonality index values of all the feature pairs of the models are shown in Tables 7.3 and 7.4.

Table 7.3 Dimensional commonality calculation for the coffeemaker lower housing

Component name	Dimensional commonality	
BBB feature-pair	$(DC)_{BBB} = 0$; the feature-pair are not of same type in terms of geometry	
LRE feature-pair	$(DC)_{LRE} = 0$; the feature-pair are not of same type in terms of geometry	
Warming plate extrusion (WPC) feature-pair Number of features to be compared, $n=2$ Number of different dimensions, $t=2$	Radius $d_{11} = 50; d_{12} = 50; d_{1m} = 50$ $deld_1 = \frac{1}{(2-1)}\left(\frac{50-50}{50}+\frac{50-50}{50}\right) = 0$ $d_1 = 1-0 = 1$ $(DC)_{WPC} = \frac{1}{2}(1+1) = 1$	Depth $d_{21} = 2; d_{22} = 2; d_{2m} = 2$ $deld_2 = \frac{1}{(2-1)}\left(\frac{2-2}{2}+\frac{2-2}{2}\right) = 0$ $d_2 = 1-0 = 1$
Upper opening cut (UOC) feature-pair	$(DC)_{UOC} = 0$; the feature-pair are not of same type in terms of geometry	
Shell (S) feature-pair Number of features to be compared, $n=2$ Number of different dimensions, $t=1$	Shell thickness $d_{11} = 2; d_{12} = 2; d_{1m} = 2$ $deld_1 = \frac{1}{(2-1)}\left(\frac{2-2}{2}+\frac{2-2}{2}\right) = 0$ $d_1 = 1-0 = 1$ $(DC)_S = \frac{1}{1}(1) = 1$	

Table 7.4 Positional commonality calculation for the coffeemaker lower housing

Component	Commonality in *X*	Commonality in *Y*	Commonality in *Z*
Basic building block (BBB) feature-pair Number of features to be compared, $n=2$	$CX_1 = 113.75$ $CX_2 = 113.50$ $CX_m = 113.75$ $delX = \frac{1}{(2-1)}\left(\frac{0+0.25}{113.75}\right)$ $= \frac{0.25}{113.75}$	$CY_1 = 62.50$ $CY_2 = 62.50$ $CY_m = 62.50$ $delY = \frac{1}{(2\text{-}1)}\left(\frac{0+0}{62.5}\right)$ $= 0$	$CZ_1 = 20$ $CZ_2 = 20$ $CZ_m = 20$ $delY = \frac{1}{(2\text{-}1)}\left(\frac{0+0}{20}\right)$ $= 0$
	$(del)_{BBB} = Avg\left(\frac{0.25}{113.75}+0+0\right) = 0.00073 \quad (PC)_{BBB} = 1-0.00073 = 0.99$		
Lower reservoir extrusion (LRE) feature-pair Number of features to be compared, $n=2$;	$CX_1 = 46.14$ $CX_2 = 31$ $CX_m = 46.14$ $delX = \frac{1}{(2\text{-}1)}\left(\frac{15.14+0}{46.14}\right) = \frac{15.14}{46.14}$		
	$(del)_{LRE} = Avg\left(\frac{15.14}{46.14}+0+\frac{0.50}{92.50}\right) = 0.11 \quad (PC)_{LRE} = 1\text{-}0.11 = 0.89$		

Table 7.4 Continued

Component	Commonality in X	Commonality in Y	Commonality in Z
Warming plate cut (WPC) feature-pair Number of features to be compared, $n=2$	$CX_1 = 137.50$ $CX_2 = 137$ $CX_m = 137.50$ $delX = \frac{1}{(2-1)}\left(\frac{0+0.50}{137.50}\right) = \frac{0.50}{137.50}$ $(del)_{WPC} = Avg\left(\frac{0.50}{137.50}+0+0\right) = 0.0012$ $(PC)_{WPC} = 1-0.0012 = 0.99$		
Upper opening cut (UOC) feature-pair Number of features to be compared, $n=2$	$CX_1 = 46.14$ $CX_2 = 31$ $CX_m = 46.14$ $delX = \frac{1}{(2\text{-}1)}\left(\frac{15.14+0}{46.14}\right) = \frac{15.14}{46.14}$ $(del)_{UOC} = Avg\left(\frac{15.14}{46.14}+0+\frac{5}{144}\right) = 0.12$ $(PC)_{UOC} = 1\text{-}0.12 = 0.88$		
Shell (S) feature-pair Number of features to be compared, $n=2$	$(PC)_S = 0.99$; Shells and basic building block have same geometric centers.		

7.3.2.2 Platform Indices

All individual *DC* and *PC* values for each feature-set need to be combined to determine the platform indices and to help designers with platform decisions. Since there are no established platform indices or measures to calculate commonality for a set of products, in this chapter a simple hierarchical index has been proposed.

The proposed platform index starts with the calculated dimensional and positional commonality values. First, the designer decides on the set of components (other than identical components) that have the potential to be part of the common platform. This decision is a two step process: (1) since all features of a component set may not be identical, but can be very similar in terms of manufacturing process, rather than looking for the perfectly identical components for a common platform, a suitable platform index can be developed to accommodate the differences. Similarly the platform index values for different sets of components can be used to develop assembly platform indices for a set of products; and (2) components that may be slightly different in terms of geometry and dimension, can be made similar with minor changes in design to accommodate them into a common platform. The platform index developed here can be used to identify components, which have the potential to be in a common platform at present, or in the future. In this research, a hierarchical approach (Figure 7.5) is used to develop the average component platform commonality index (ACPCI) and average assembly platform commonality index (AAPCI). Using CAD software, the models have to be created following a specified sequence (Figure 7.6) of operations. A final product is an assembly of a number of components. Hence, the components have to be modeled before creating the final assembly. Components are accumulation of various features (basic building block, extrusion, cut, revolve, *etc*.), which have certain geometry with specific dimensions. The feature geometries are created using sketches.

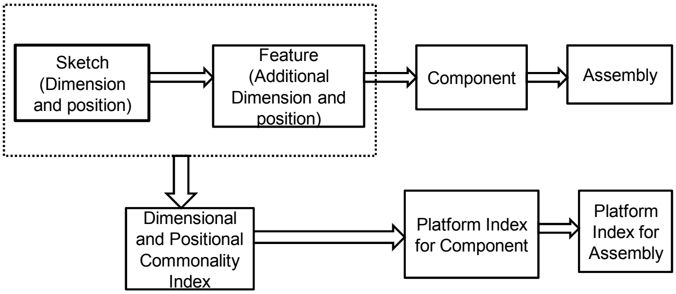


Figure 7.5 Hierarchical approach to develop the platform commonality index

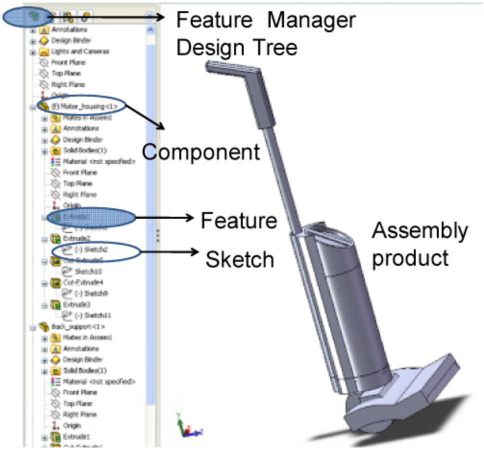


Figure 7.6 Sequential set of operations in the SolidWorks environment

The dimensional and positional commonality values, derived from a feature-set, are used to develop the ACPCI which will be then used to develop the AAPCI. Higher dimensional and positional commonality values for feature sets will result in higher ACPCI for a set of components. A higher ACPCI value for the component sets results in higher probability for the components to be in the common platform. Here the dimensional and positional commonality indices for each feature are averaged to calculate ACPCI. The maximum possible value of ACPCI is 1, when all elements in the feature set are identical. Similarly the maximum possible AAPCI is 1, when all components in the assemblies are identical. The ACPCI is determined based on how much the average commonality values for the individual feature set are offset from the maximum possible value, which is 1. The summation of all the offset values gives the total offset values for all the feature-sets among a given component-set. The average of the total offset values can be calculated dividing the summation by the total number of feature-sets used in the given component-set. The ACPCI will be the difference between the maximum possible average platform index and the total average platform index.

$$ACPCI = \left\{1 - \frac{1}{NOF}\sum\left(1 - AC\right)\right\} \times 100\% \tag{7.3}$$

where:

NOF = number of feature-sets in a given component-set

AC = average commonality for a feature-set.

The maximum possible value of ACPCI is 100%, when all components in a given component-set are identical and the minimum possible value will be zero, when the components are totally different.

The AAPCI for a set of products is calculated similarly, using the ACPCI values of component-sets in the given product-set.

$$AAPCI = \left\{1 - \frac{1}{NOC}\sum\left(1 - ACPCI\right)\right\} \times 100\% \tag{7.4}$$

where:

NOC = number of component-sets in a given product-set.

The maximum possible value of AAPCI will be 100%, when all the products in a given product-set are identical in respect to all characteristics measured and the minimum possible value will be zero, when the products are totally different.

7.4 Case Studies

Two case studies are presented in this section to illustrate the proposed method for common component and platform identification from 3D CAD models of components.

7.4.1 Case Study 1 – Cell Phone Casings Product Platform

The first case study focuses only on the component commonality measurement. The capability of the method and algorithms to compare 3D solid models is demonstrated by comparing cell phone covers. The calculated commonality indices are then used to determine the potential of the cell phone covers, used in the component-set, to be in a common component platform.

The case study analyses two cellular phone top casings. For simplicity, the number of casings in the component-set is restricted to two. The cell phone top casings are selected for this case study as they have a number of features for the buttons, the display screen, the speaker, and snap fits. The dimensions of the slots and the basic building blocks are different for the two casings.

Casing model 1 (Figure 7.7) has a shell thickness of 2 mm. All slots except for the snap fit slots, are through holes (depth = 2 mm). The depths of all the snap-fit slots are 5 mm. The snap fits are located symmetrically at the center locations of their respective faces. Casing model 2 (Figure 7.8) has a shell thickness of 2 mm. Dimensions of the features in the second casing are similar to the ones in the first casing.

The list of features in model 1 is (Figure 7.7):

1. Snap fit grooves 4 and 5 have the same dimensions;
2. Buttons 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18 have the same dimensions;
3. Buttons 21 and 22 have the same dimensions;
4. Buttons 23 and 24 have the same dimensions.

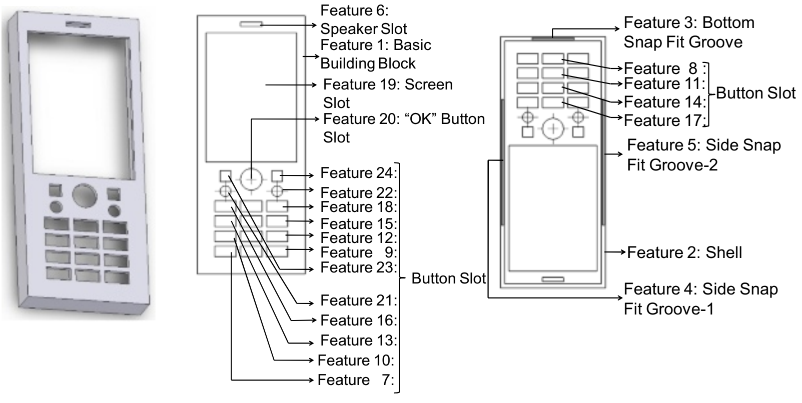


Figure 7.7 Cell phone casing model 1: (a) isometric view, (b) top view, and (c) bottom view

The list of features in model 2 is (Figure 7.8):

1. Snap fit grooves 4 and 5 have the same dimensions;
2. Buttons 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18 have the same dimensions;
3. Buttons 21 and 22 have the same dimensions;
4. Buttons 23 and 24 have the same dimensions.

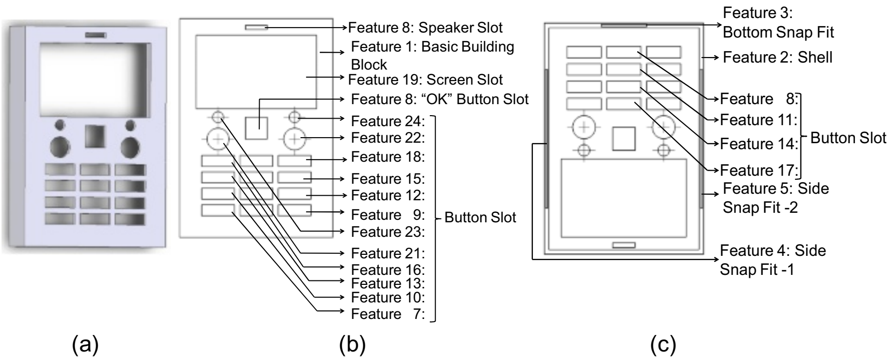
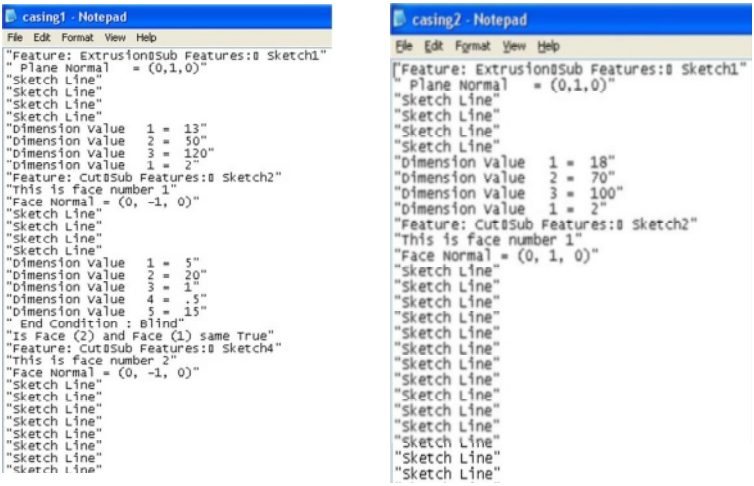


Figure 7.8 Cell phone casing model 2: (a) isometric view, (b) top view, and (c) bottom view

The features in each model are numbered as given in the feature lists and each feature in casing model 1 is compared with its corresponding feature in casing model 2. In other words, feature 1 in casing model 1 is compared with feature 1 in casing model 2; feature 2 in casing model 1 is compared with feature 2 in casing model 2, and so on. In this chapter it is assumed that the designer/user will provide this information.

The cell phone casings are modeled using SolidWorks. A SolidWorks macro, written in Visual Basic, is utilized to extract the entire feature, dimension, and position information from the models. Information from the models is stored in separate TEXT files. The information in the TEXT files is used to calculate the dimensional and positional commonality of the feature pairs. The screen shots of the TEXT files for the Cell phone casings are shown in Figure 7.9.



```
"Feature: Extrusion□Sub Features:□ Sketch1"
"  Plane Normal    = (0,1,0)"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Dimension Value   1 =  13"
"Dimension Value   2 =  50"
"Dimension Value   3 =  120"
"Dimension Value   1 =  2"
"Feature: Cut□Sub Features:□ Sketch2"
"This is face number 1"
"Face Normal = (0, -1, 0)"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Dimension Value   1 =  5"
"Dimension Value   2 =  20"
"Dimension Value   3 =  1"
"Dimension Value   4 =  .5"
"Dimension Value   5 =  15"
"  End Condition : Blind"
"Is Face (2) and Face (1) same True"
"Feature: Cut□Sub Features:□ Sketch4"
"This is face number 2"
"Face Normal = (0, -1, 0)"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
```

Casing Model 1

```
"Feature: Extrusion□Sub Features:□ Sketch1"
"  Plane Normal    = (0,1,0)"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Dimension Value   1 =  18"
"Dimension Value   2 =  70"
"Dimension Value   3 =  100"
"Dimension Value   1 =  2"
"Feature: Cut□Sub Features:□ Sketch2"
"This is face number 1"
"Face Normal = (0, 1, 0)"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
"Sketch Line"
```

Casing Model 2

Figure 7.9 Partial text file screen shot extracted for cell phone casing models

Positional and dimensional commonality indices for all features in the two casings are shown in Table 7.5. The ACPCI (using (7.3)) for the model pair is 78.02%. The result obtained is quite high since most of features in the casing pair are similar.

Table 7.5 Commonality results for the cell phone cover case study

Feature no.	Description	Dimensional commonality	Positional commonality	Average commonality	Offset from maximum	ACPCI (%)
1	Basic building block	0.76	0.88	0.82	0.18	–
2	Shell	0.74	0.89	0.815	0.185	–
3	Bottom snap fit groove	1	0.93	0.965	0.035	–
4	Side snap fit - 1 groove	1	0.95	0.975	0.025	–
5	Side snap fit - 2 groove	1	0.81	0.905	0.095	–
6	Speaker slot	1	0.84	0.92	0.08	–
7	Button slot	0.89	0.96	0.925	0.075	–
8	Button slot	0.89	0.92	0.905	0.095	–
9	Button slot	0.89	0.88	0.885	0.115	78.02
10	Button slot	0.89	0.96	0.925	0.075	–
11	Button slot	0.89	0.92	0.905	0.095	–
12	Button slot	0.89	0.88	0.885	0.115	–
13	Button slot	0.89	0.95	0.92	0.08	–
14	Button slot	0.89	0.92	0.905	0.095	–
15	Button slot	0.89	0.88	0.885	0.115	–
16	Button slot	0.89	0.95	0.92	0.08	–
17	Button slot	0.89	0.91	0.9	0.1	–
18	Button slot	0.89	0.87	0.88	0.12	–
19	Screen slot	0.77	0.9	0.835	0.165	–
20	"OK" button slot	0	0	0	1	–
21	Button slot	0.75	0.94	0.845	0.155	–
22	Button slot	0.75	0.86	0.805	0.195	–
23	Button slot	0	0	0	1	–
24	Button slot	0	0	0	1	–

7.4.2 Case Study 2 – Coffeemaker Product Platform

The second case study focuses on identifying the common platforms for a set of coffeemakers. The Average AAPCI is calculated to decide whether the assembly can be considered for the common platform. Components of the coffeemakers, which have the potential to be accommodated in the common platform, will be determined through the ACPCI calculation.

Two coffee makers are analyzed in the case study. The number is restricted to two for simplicity. During the modeling, insignificant aesthetic features (such as fillets, chamfers, *etc.*) are not considered. It is assumed that the designer will follow the same sequence of feature creation when making the component models. Both models (Figures 7.10 and 7.11) are comprised of: (1) lower housing, (2) upper housing, (3) upper end cover, (4) lower end cover, (5) heater, (6) heating tube, (7) warming plate, (8) filter, (9) electric circuit, and (10) condensing tube.

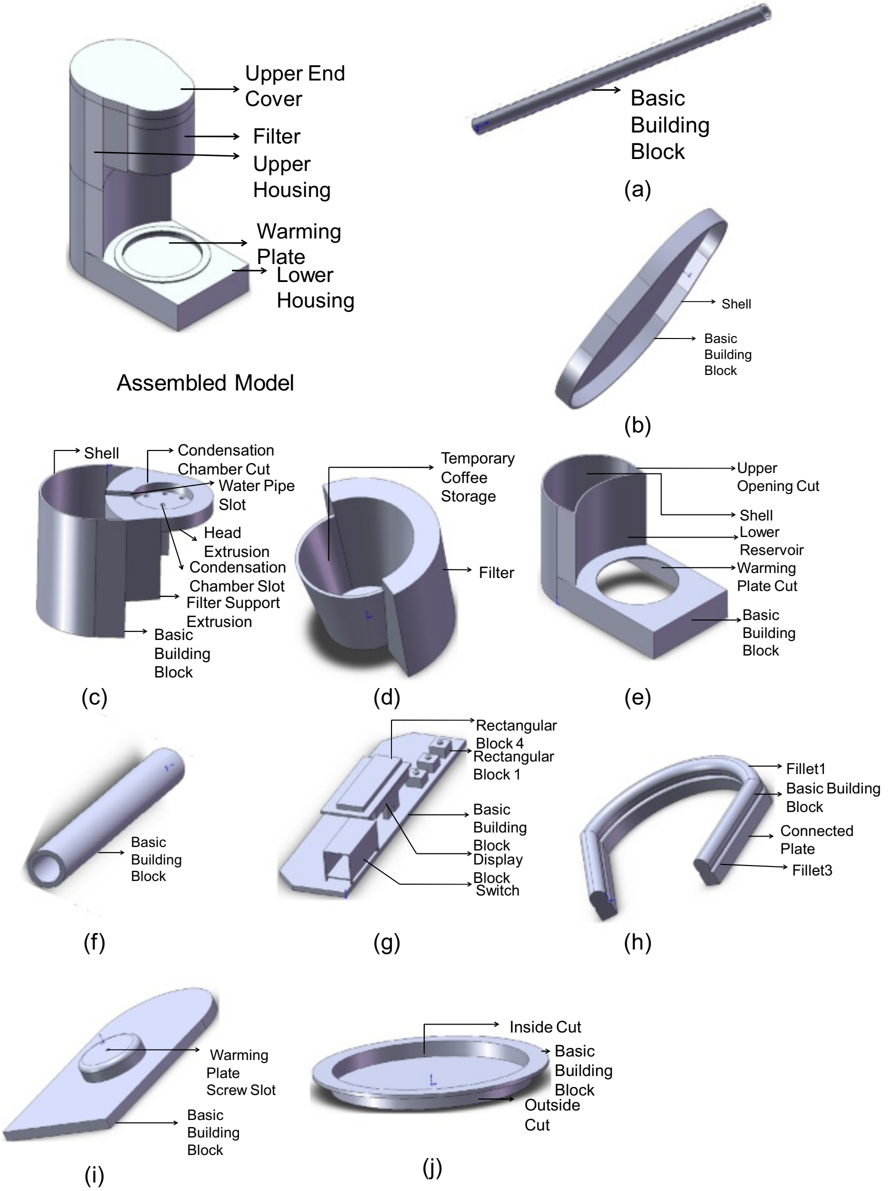


Figure 7.10 Coffeemaker 1 assembly and component: condensing tube (a), upper end cover (b), upper housing (c) , filter (d), lower housing (e), heating tube (f), electric circuit (g), heater (h), lower end cover (i), and warming plate (j)

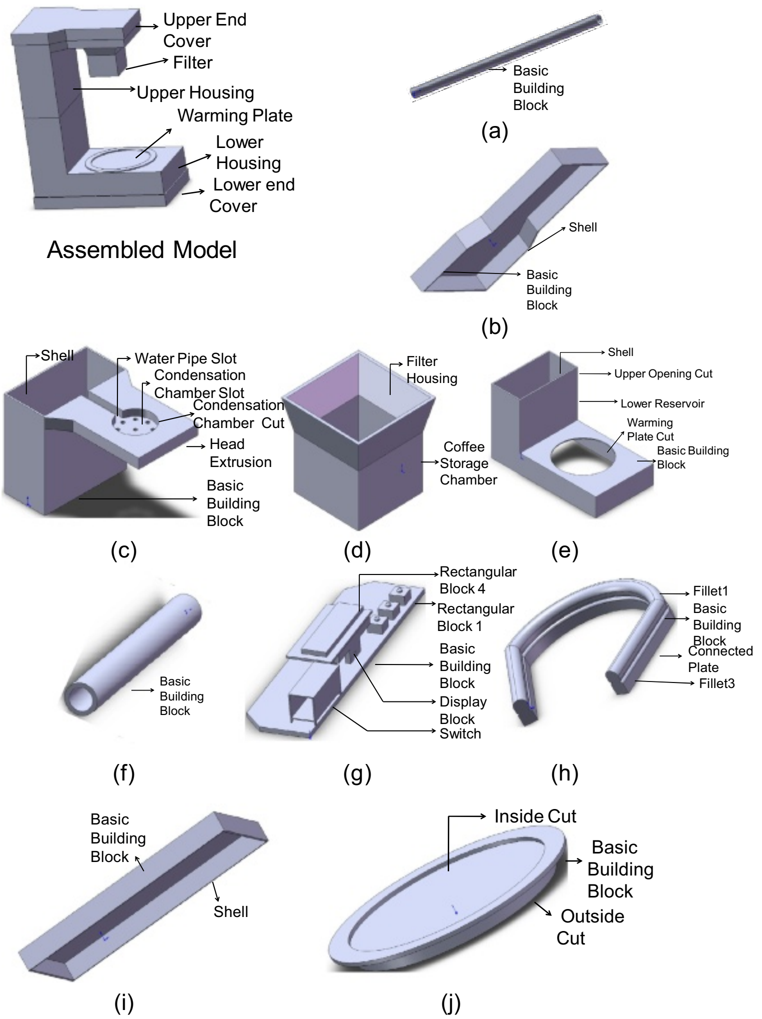


Figure 7.11 Coffeemaker 2 assembly and components: condensing tube (a), upper end cover (b), upper housing (c), filter (d), lower housing (e), heating tube (f), electric circuit (g), heater (h), lower end cover (i), and warming plate (j)

All components are modeled using SolidWorks and then assembled to complete the 3D model of the coffeemaker. The corresponding CAD models of the components are compared and the ACPCI is calculated for each component set. The information needed to calculate the positional and dimensional commonality, are extracted from the models using the macro mentioned in Case Study 1. As an example, consider the warming plate component (Figures 7.10j and 7.11j) with the following features: (1) basic building block, (2) inside cut, and (3) outside cut. The calculated ACPCI is 89.33% (Table 7.6).

The upper housing components (Figures 7.10c and 7.11c) of the coffeemakers have a total of 16 features. Although the outer geometry of the component varies significantly, some of the inner features have high positional and dimensional commonality. The ACPCI (using (7.3)) for the component set is 75.19% (Table 7.7).

Table 7.6 Commonality results for the warming plate component set

Feature no.	Description	Dimensional commonality	Positional commonality	Average commonality	Offset from maximum	ACPCI (%)
1	Basic building block	1	1	1	0	–
2	Inside cut	0.42	0.94	0.68	0.32	89.33
3	Outside cut	1	1	1	0	–

Table 7.7 Commonality results for upper housing components set

Feature No.	Description	Dimensional commonality	Positional commonality	Average commonality	Offset from maximum	ACPCI (%)
1	Basic building block	0	0.89	0.445	0.555	–
2	Shell	1	0.84	0.92	0.08	–
3	Head extrusion	0	0.98	0.49	0.51	–
4	Filter support extrusion	0	0	0	1	–
5	Water pipe slot	0	0.97	0.485	0.515	–
6	Condensation chamber cut	0.92	0.96	0.94	0.06	75.19
7	Condensation chamber slot1	1	0.94	0.97	0.03	–
8	Condensation chamber slot2	1	0.93	0.965	0.035	–
9	Condensation chamber slot3	1	0.94	0.97	0.03	–
10	Condensation chamber slot4	1	0.96	0.98	0.02	–
11	Condensation chamber slot5	1	0.96	0.98	0.02	–
12	Condensation chamber slot6	1	0.95	0.975	0.025	–
13	Condensation chamber slot7	1	0.92	0.96	0.04	–
14	Condensation chamber slot8	1	0.92	0.96	0.04	–
15	Condensation chamber slot9	1	0.98	0.99	0.01	–
16	Lower filter slot	0	0	0	1	–

Table 7.8 Average assembly platform commonality index (AAPCI) for the coffeemaker family

Name	Average component platform commonality index (ACPCI)	c	Average assembly platform commonality index (AAPCI), (%)
Upper housing	0.75	0.25	–
Lower housing	0.67	0.33	–
Upper end cover	0.69	0.31	–
Lower end cover	0.46	0.54	74.6
Warming plate	0.89	0.11	–
Heater	1	0	–
Electric circuit	1	0	–
Condensation tube	1	0	–
Heater tube	1	0	–
Filter	0	1	–

All ACPCI values for the entire component-sets are shown in Table 7.8. The ACPCI values are then used to determine the AAPCI (using (7.4)), which is 74.6%. Both coffeemaker assemblies are compared without the coffeepots.

From the calculated ACPCI, it can be observed that four components are identical for both coffeemakers; consequently the resulting AAPCI value of 74.6% (Table 7.8) is very high. The result obtained in the case study is reasonable. However, two of the components [filter, Figures 7.10 and 7.11d, and lower end cover, Figures 7.10i and 7.11i) have very low values of ACPCI. If ACPCI of 65% is considered as the threshold for the components to have the potential to be modified to be common, then eight components out of ten will be accommodated in the common platform. The designer will decide the threshold value of the ACPCI depending on his or her preference.

From Table 7.8 it can be observed that four components (upper housing, Figures 7.10c and 7.11c, lower housing, Figures 7.10e and 7.11e, upper end cover, Figures 7.10b and 7.11b, and warming plate, Figures 7.10j and 7.11j) have ACPCI values between 0.65 and 1. The components can be made identical with minor design changes and the ACPCI values can be improved to 1. Eventually, the AAPCI value for the Coffeemaker models can be improved to 84.6%. This increase in commonality will make the two coffeemakers almost the same product, which is not desired. Out of the four component sets upper housing, lower housing and upper end cover cannot be changed because they provide varieties among the coffeemaker models. Since warming plates do not provide any kind of variety among models, they can be made identical. The AAPCI value with the identical warming plates can be improved as high as 75.7%.

7.5 Concluding Remarks

In this chapter, a *shape commonality* comparison between mechanical components is presented to facilitate the development of common platform. An approach is proposed by which the dimension and position of every feature in the component models are compared and the commonality is expressed quantitatively. This process is repeated for all dimensions of the particular feature and all commonality measures are combined to yield the ACPCI and the AAPCI for a particular set of components and assemblies respectively. A Hierarchical approach for CAD models is proposed to calculate ACPCI and AAPCI.

Two case studies are presented to demonstrate the capability of the algorithms and equations developed. In order to determine component commonality, a macro has been written to extract all the information from the CAD models. Visual Basic is used to write the macro, which utilized the API functions of SolidWorks to communicate with various features of the CAD software.

However, there are some *limitations* to the proposed approach. Designers are assumed to give all the information needed to calculate the dimensional and positional commonality for a set of features. The designers have to follow same sequence in creating the features for all the components in the set. All positional dimensions for every feature in a component need to be specified from the same reference. This is not always possible, especially for complex CAD models. The information in the text files extracted from the model is very difficult to sort for models that have very complex geometry. The number of API available in the SolidWorks library is not enough to extract all detailed information from the CAD models. It cannot extract information for some of the features of SolidWorks. This also limits the independence of the designer.

The comparison process is currently being automated to lessen the manual effort, which will aid in the development of a 3D CAD search engine. An algorithm may be developed to search for similar components from the web by checking the similarity among the components. With the advent of outsourcing, industries are now located in different regions and designers around the world are working on the same product. One way to achieve fast and efficient design process is through collaboration among designers working in a common field. Interactions among them can prevent redesign of similar components or sub-systems. Designers need to be able to share their design to ensure a faster design process. Large databases of 3D CAD models are already being developed by many companies. An efficient and faster search process to identify common models will ensure the best utilization of such databases. The proposed method may be extended to incorporate a search algorithm for CAD models.

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Chapter 8
A Platform Identification Method for Service Family Design Using a Process Model and a Clustering Method

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Abstract The objective in this research is to introduce a method for identifying a service platform along with variant and unique modules to create a service family by integrating object-oriented concepts, ontologies, and data mining techniques. A service process model is introduced to describe a service based on a sequence using a graph model and object-oriented concepts. Fuzzy clustering is employed to partition service processes into subsets to identify common modules – the platform – and specific modules for the given service family. To demonstrate the proposed method, we apply it to select a platform for a family of banking services.

Abbreviations

CN	Customer need
FCM	Function-component matrix
FPM	Function-process matrix

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FR	Functional requirement
PC	Partition coefficient
UML	Unified modeling language

8.1 Introduction and Background

For mass customization, companies are increasing their efforts to reduce cost and lead-time when developing new products and services while satisfying individual customer needs. Mass customization depends on a company's ability to provide customized products or services based on economical and flexible development and production systems (da Silveira *et al.* 2001). By sharing and reusing assets such as components, processes, information, and knowledge across a family of products and services, companies can efficiently develop a set of differentiated economic offerings by improving flexibility and responsiveness of product and service development (Simpson, 2004). Product family design is a way to achieve cost-effective mass customization by allowing highly differentiated products to be developed from a common platform while targeting products to distinct market segments (Shooter *et al.* 2005).

A product family is a group of related products based on a product platform (Simpson *et al.* 2005). A product platform is the set of features, components or subsystems that remain constant from product to product, within a given product family. A successful product family depends on how well the trade-off between the economic benefits and performance losses incurred from having a shared platform are managed. For instance, high levels of commonality decrease interface and component costs while increasing customers' preference loss.

Services are an important source of revenue for many companies, since products can be paired with additional services to satisfy customers' needs, differentiate product offerings, and remain competitive in today's market. Service science research seeks to improve the productivity and quality of service by creating new innovations, facilitating business management, and applying practical applications (Hidaka 2006). Recently, theories and methodologies for mass-customized products are being applied to service development (Jiao *et al.* 2003), and the concept of product family design, in particular, provides good solutions to various customized service industries (Peters and Saidin 2000, Meyer and Detore 2001, Jiao *et al.* 2003). For example, in the IBM Malaysia service unit, modularization of the scope of work and processes has been applied to service level design for mass customization (Peters and Saidin 2000). Lincoln Re used platform concepts to develop new insurance services (Meyer and Detore, 2001). In this chapter, we extend concepts from platform-based product families to create a new approach for module-based service family design.

The objective in this research is to introduce a method to identify a service platform along with variant and unique modules in a service family by integrating object-oriented concepts, ontologies, data mining techniques, and fuzzy set theory.

Object-oriented concepts provide service analysis tools for describing a business process or a workflow process in a service (Arlow and Neustadt 2002, Hoffer *et al.* 2006). A function-process matrix is used to identify the relationships between the service functions and the service processes that are offered as part of a service. An ontology is applied to define properties that consist of attributes and behaviors for representing a service in a service hierarchical structure. A service process model is introduced to describe a service based on a sequence using a graph model and object-oriented concepts.

Data mining can be used to help identify customer needs, to find relationships between customer needs and functional requirements, and to cluster products based on functional similarity to facilitate modular design (Braha 2001). Fuzzy c-means clustering (FCM) (Bezdek 1981) is employed to partition service processes into subsets to identify a platform and modules in a given service family. The clustering results provide membership values that represent the corresponding membership level of each cluster, which can be considered as the degree of similarity among process features. Fuzzy set theory (Zadeh 1965) is used to determine platform levels that represent the membership values.

The remainder of this chapter is organized as follows. Section 8.2 describes the proposed method for identifying a service platform and service modules. Section 8.3 gives a case study using a family of banking services. Closing remarks and future work are presented in Section 8.4.

8.2 Method for Service Module and Platform Identification

To develop customized services, we propose the following definitions for service family design:

1. A service family is a set of services based on a service platform, facilitating mass customization by promoting customer value and providing a variety of services for different market segments cost-effectively.
2. A service platform is a common basis that consists of processes, activities, objects, and/or features that are shared and remain constant from service to service, within a given service family.
3. A service module is a set of service components for performing a service.
4. A service component is regarded as an activity to satisfy certain services, which are defined by a set of processes, operations, people, objects, and/or features.

These definitions provide a foundation for modeling customized families of services. Based on these definitions, we extend concepts from platform-based product family design to develop a module-based service family. A service platform consists of common service modules that are defined as service components representing functions and processes. Based on the service platform, we can create a variety of services and families of services for satisfying various market segments depending on service-related design factors such as location, facility

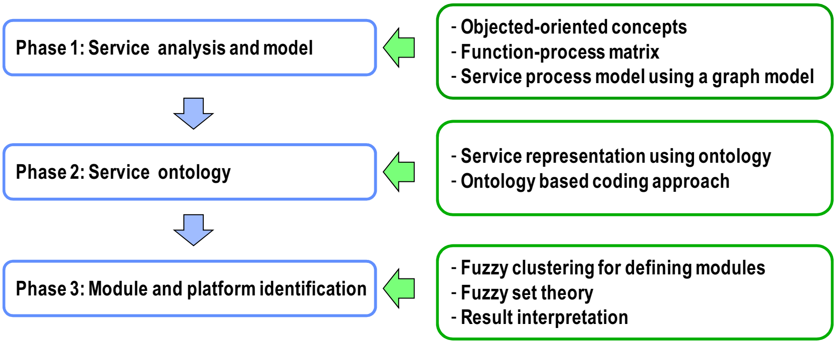

Figure 8.1 Proposed method for service module and platform identification

design and layout for effective customer and work flow, procedures and job definitions for service providers, measures to ensure quality, extent of customer involvement, equipment selection, and adequate service capacity (Fitzsimmons and Fitzsimmons 2004).

In this chapter, we introduce a method for identifying a platform along with variant and unique modules in service families using object-oriented concepts, ontologies, and data mining. Figure 8.1 shows the flow diagram of the proposed method that consists of three phases: (1) service analysis and model, (2) service ontology, and (3) module and platform identification. The next section discusses each phase of the method in detail.

8.2.1 Phase 1: Service Analysis and Model

8.2.1.1 Service Selection and Analysis

Figure 8.2 shows the process for developing a family of services based on a customer-driven approach. Information required to identify customer needs (CNs) can be collected by surveying prospective customers and by conducting a marketing study that begins by establishing target markets and customers. In the initial phase, CNs are analyzed to understand customer intention and determine a strategy for developing a service family. For example, the number of services can be decided by customer groups and classified according to CNs. CNs are also used to identify appropriate functional requirements (FRs), which are then mapped to the CNs. In service design, FRs represent processes and capabilities that can be determined by work flow, procedures and job definitions for service providers, and service quality. During conceptual design, services can be designed based on FRs, and their functional modules can also be determined. In particular, a family of services is first configured by defining a service platform. A service platform consists of several common modules that can be shared across a family of ser-

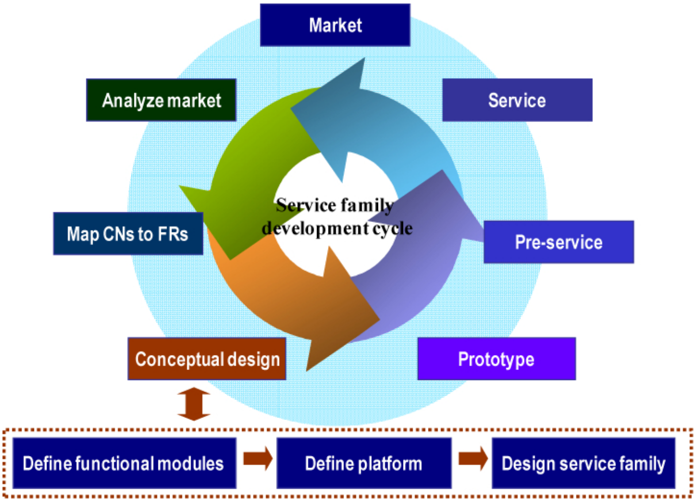

Figure 8.2 Service family design process

Table 8.1 A function-process matrix for service analysis

Process module Functional module	Process 1	Process 2	.	.	.	Process *m*
Function 1	1					1
Function 2		1				1
.			.	.	.	1
.			.	.	.	
.			.	.	.	1
Function *n*		1				

vices. After conceptual design, through prototype and pre-service processes, final services are delivered.

Object-oriented concepts can be used to analyze service processes and identify service design factors. Object-oriented design and analysis methodologies are used to develop information systems by modeling a system as a set of objects in the area of software engineering and business (Schach 2004). Through service analysis using objected-oriented concepts, we can determine service-related design factors that are represented as processes, activities, objects, and/or features, as well as service functions and processes. These design factors are also used to define the properties of service components in service process model design.

Based on service functions and processes, a function-process matrix (FPM) is introduced to identify the relationships between functional modules and process modules in a service. The FPM is similar to the FCM (Strawbridge *et al.* 2002), which provides a mapping between a product's components and its sub-functions. Table 8.1 shows a conceptual representation of the FPM. The first vertical column shows service functions, the top horizontal row is service processes and the cells of the FPM represent the relationship between each function and process. The number "1" in a cell indicates that a relationship among a function and a process exists. For example, Function 1 in Table 8.1 entails Process 1 and Process *m* to achieve this function.

8.2.1.2 Service Process Model

A business process or workflow process is described by logically related activities to achieve a defined business goal or create value-added products or services to satisfy customer needs (Reijers 2003). In services, a process can be considered as a procedure, routine, and policy to create services, which are defined by a set of activities, ordering constraints, and data or materials used for the service activities. Unified modeling language (UML) can be used to analyze service processes and/or basic workflow. UML is a standardized specification language for system design and analysis using a set of concepts, constructs, terminology, and notation (Arlow and Neustadt 2002). For example, sequence diagrams are object-interaction diagrams that consider temporal sequencing and are useful for describing the behavior of use cases and the interaction between objects within a system (Hunt 2000). Activity diagrams provide a modeling method to represent the business and operational workflows using the detailed logic of a business rule. By analyzing the sequence diagrams or the activity diagrams for a service, we can obtain attributes and identify information flow among objects for service design. For instance, suppose that the objects of a deposit process in a banking service consist of a customer, an employee, an account, and a balance. An activity diagram for the deposit process can be represented as shown in Figure 8.3. Processes in the diagram are represented by activities and attributes for performing the service.

A process model can be defined by various languages with differences in their syntax and expressive rules (Cao *et al.* 2006). A graph model is employed to describe a service process model based on service sequences. Graphs are an abstraction developed specifically to represent relationships and consist of two distinct parts: (1) nodes and (2) edges. The nodes are things in the graph that have relationships, and the edges are pairs of nodes connected by a relationship (Berry and Linoff 1997). The encapsulation concept in object-oriented concepts reduces the complexity of representing a node in service component design. As shown in Figure 8.4, a node is defined as a service component with properties that can describe service processes, and an edge as a direction presenting information, data, and materials flow. A node can be defined by five properties: (1) activity, (2) object, (3) input flow, (4) output flow, and (5) state. Activity is a process to perform a particular service by an object and is used as the name of a node. The object represents an object performing activities using input flow in certain services. The flow includes information, data, and materials, which occur in service processes.

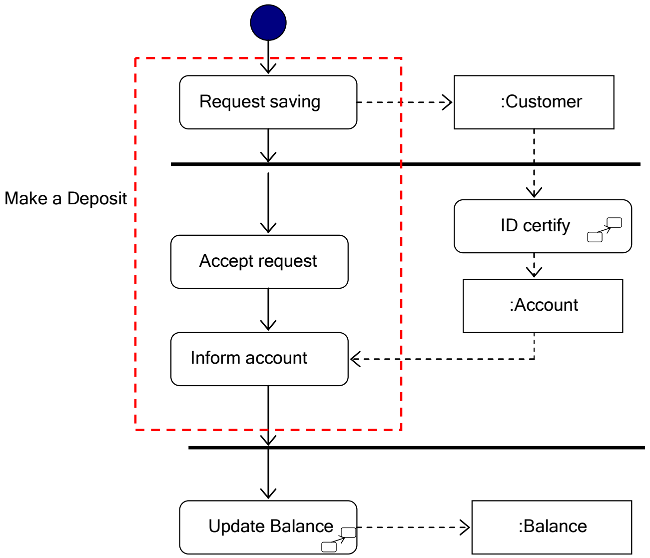

Figure 8.3 An example of an activity diagram for a banking service

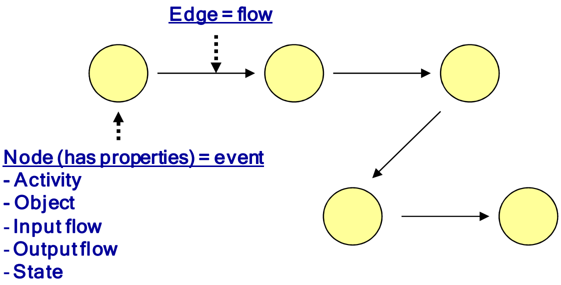

Figure 8.4 Service process model and properties for a node

States are defined as things (objects) that change the input flow and the output flow. For example, a node changes the state of its inputs (states), *i.e.,* information such as a customer's account balance or credit, materials such as money, and data in a banking service.

8.2.2 Phase 2: Service Ontology

To effectively define the relationships between functional hierarchies in a service, an appropriate representation scheme must be adopted for the services. An ontology consists of a set of concepts or terms and their relationships that describe some area of knowledge or build a representation of it (Swartout and Tate 1999).

Service ontology is developed to represent the relationships between functional modules and process modules as shown in Figure 8.5. In the service ontology, a process module has a hierarchical structure to provide process representation-based semantics of services.

The basic idea of modular design is to organize services as a set of distinct service modules that can be designed independently. Based on the concepts of the product module-based design (Kamrani and Salhieh 2000), we assume that a service can be decomposed into modules, which provide specific functions and processes. Service functions are achieved by the combination of service processes that are defined in the service ontology. Suppose that a service family consists of l services, $SF=(S_1, S_2, ..., S_l)$, and a service consists of f_i functional modules, $S_i = (y_{i,1}, y_{i,2}, ... y_{i,f}, ..., y_{i,f_i})$, where $y_{i,f}$ denotes service functional module f in service i. For service processes, suppose that a service consists of m_i service process modules, $S_i = (\mathbf{x}_{i,1}, \mathbf{x}_{i,2}, ..., \mathbf{x}_{i,j}, ..., \mathbf{x}_{i,m_i})$, where $\mathbf{x}_{i,j}$ is process module j in service i and consists of a vector of length n_m, $\mathbf{x}_{ij} = (x_{i,j,1}, x_{i,j,2}, ..., x_{i,j,k}, ..., x_{i,j,n_m})$, and the individual scalar components $\mathbf{x}_{i,j,k} (k = 1, 2, ..., n_m)$ of a process module $\mathbf{x}_{i,j}$ are called process features. Each process feature consists of several attributes, $a_{i,j,k,t} (t = 1, 2, ..., t_n)$, representing the component, $x_{i,j,k} = (a_{i,j,k,1}, a_{i,j,k,2}, ..., a_{i,j,k,t}, ..., a_{i,j,k,t_n})$, where t_n is the number of properties defined in the service ontology. Figure 8.5 shows the corresponding hierarchy for representing a family of services. The identification of attributes is problem-dependent; an example can be found in the banking services case study. In this chapter, a coding approach is used to represent components' attributes for a given clustering method.

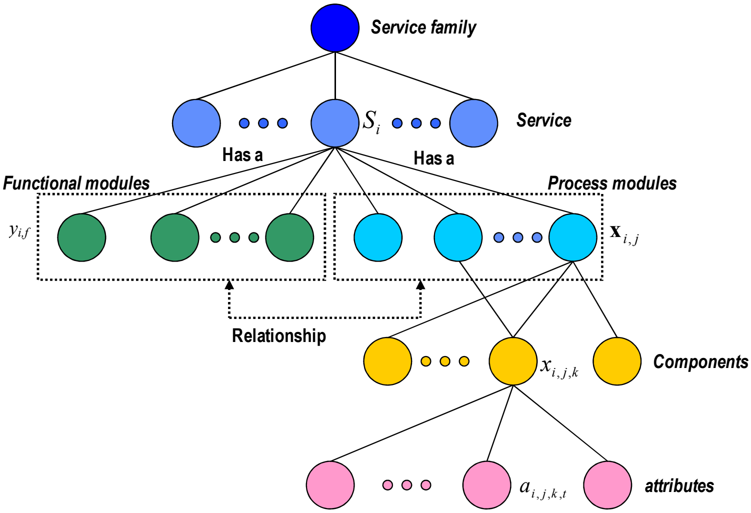

Figure 8.5 Hierarchy of the service ontology

8.2.3 Phase 3: Module and Platform Identification

8.2.3.1 Fuzzy Clustering for Defining Modules

Process decomposition for a service is often represented in a hierarchical structure as discussed in Section 8.2.2. A hierarchical clustering method can classify a set of objects by measuring the similarity between objects (Miyamoto 1990). Because heuristic methods for defining a module may provide overlapping or non-crisp boundaries among module clusters (Stone *et al.* 2000), the results of traditional clustering approaches are not appropriate to define clusters as modules in service design. Moreover, since design information for a service depends on the experience and knowledge of designers, design information, such as linguistic terms, may fail to describe a crisp representation completely. When clustering design information we need to assign the information to clusters with varying degrees of membership. Fuzzy membership can provide proper representation while also capturing the fuzziness of design knowledge (Braha 2001). Fuzzy clustering approaches can use fuzziness related to design features and provide more useful solutions (Xue and Dong 1997, Liao 2001). We employ FCM (Bezdek, 1981) to determine clusters for identifying modules for the service family. FCM is a clustering technique that is similar to k-means but uses fuzzy partitioning of data that is associated with different membership values between 0 and 1. Since FCM is an iterative algorithm, its aim is to find cluster centers that minimize a dissimilarity function.

Let $\mathbf{x}_k$ for $k = 1, 2, ...n$ be a process feature and a d-dimensional vector (d is the number of attributes), and $u_{i,k}$ the membership of $\mathbf{x}_k$ to the ith cluster $(i = 1, 2, ..., c)$. The $u_{i,k}$ representing a fuzzy case is between 0 and 1. For example, if $u_{i,k} = 0$, $u_{i,k}$ has non-membership to cluster i, and if $u_{i,k} = 1$, then it has full membership. Values between 0 and 1 indicate fractional membership. Generally, FCM is defined as the solution of the following minimization problem (Bezdek 1981):

$$J_{FCM}(U, V) = \{\sum_{i=1}^{c}\sum_{k=1}^{n}(u_{ik})^m \left\|X_k - v_i\right\|^2\} \tag{8.1}$$

subject to:

$$\sum_{i=1}^{c} u_{ik} = 1 \text{ for all } k \tag{8.2}$$

$$u_{ik} \in [0, 1] \tag{8.3}$$

where v_i is the cluster center of the ith cluster that consists of a d-dimensional vector, and m is a parameter $(m \geq 1)$ that indicates the fuzziness of the clusters. We use the FCM algorithm from Bezdek (1981) and Torra (2005) in this work. While this algorithm does not ensure convergence to a global optimum, it always converges to a local optimum that may lead to different local minima when using a different initial number of cluster centers.

In this FCM algorithm, since the cluster number c is determined before clustering, a validity index for an optimal c should be considered for defining the number of clusters. In this chapter, the partition coefficient (PC) is used to determine the best cluster number c (Bezdek 1974):

$$PC(c) = \frac{1}{n}\sum_{i=1}^{c}\sum_{k=1}^{n} u_{ik}^{2} \tag{8.4}$$

where $1/c < \mathrm{PC}(c) < 1$. An optimal cluster number c^* maximizes PC(c), (the number of services + 1) $< c < n-1$.

The cluster number determines the number of modules. A maximum membership value in clusters is an indicator for assigning to a module that can be considered as a group of similar process features. Among clusters, clusters including the process features for all selected services become common modules for the platform.

8.2.3.2 Platform Level Determination

Since membership values from the results of clustering represent the degree of similarity among process features, we can consider the membership values as the corresponding membership level of each cluster. Based on fuzzy set theory (Zadeh 1965), membership values are measured using a rating scale of [0–1], and the ratings can be interpreted as fuzzy numbers based on different platform levels, such as low, medium, and high. Let X be a linguistic variable with the label "platform level" with $U = [0, 1]$, and three fuzzy terms for the linguistic variable are defined as low (x_1), medium (x_2), and high (x_3) as shown in Figure 8.6. The membership function of each fuzzy set is assumed to be triangular, and the platform level can take three different linguistic terms. Platform level membership functions are proposed to represent and determine the platform level of a common module. Therefore, the membership values of functions in a common module are transferred into platform level values by the platform level membership functions. The platform level of the common module is determined by the maximum value among average membership level values for the module. For example, suppose two processes, A and B, are in a common module. If the membership values of the two processes are 0.4 and 0.6, then the platform level values of the value 0.4 are represented by 0 at high, 0.8 at middle, and 0.2 at low, while the platform level values for the 0.6 value are represented by 0.2 at high, 0.8 at middle, and 0 at low.

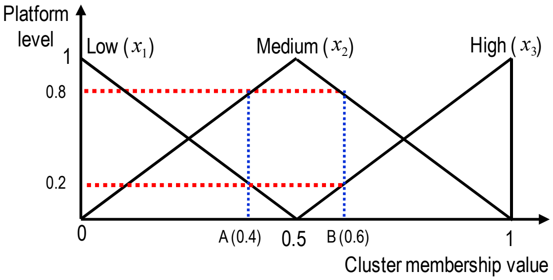

Figure 8.6 Fuzzy membership function representing platform level

Therefore, the platform level of the common module is determined as the middle level (*i.e.*, 0.1 at high, 0.8 at middle, and 0.1 at low).

8.2.3.3 Interpretation of Results

The final results determine the service platform along with the variant and unique modules for the service family, where the platform consists of common modules with a high platform level. If variant modules are selected as part of the platform, additional process features will be required to make them a common module. The service ontology is used to identify the meaning of modules using the relationship between service functions and processes. During conceptual design, these results can help decision-makers define the set of modules for the service family. The effective set of modules will lead to improved service family design. Additionally, since the proposed method uses the similarity of process features, we can evaluate the commonality of existing services by the membership values of clusters. A case study is presented next to demonstrate the proposed method.

8.3 Case Study

Consider a family of banking services consisting of four checking account services as shown in Table 8.2. The checking account services are designed for four differ-

Table 8.2 Four checking account services in a banking service family[5]

Option	Service A	Service B	Service C	Service D
Deposit	Yes	Yes	Yes	Yes
Withdraw	Yes	Yes	Yes	Yes
Transfer	Yes	Yes	Yes	Yes
Banking statement	Yes	Yes	Yes	Yes
Online account statement	Yes	Yes	Yes	Yes
Checking writing	Yes	Yes	Yes	Yes
ATM transactions	Yes	Yes	Yes	Yes
Online banking with bill pay	Yes	Yes	Yes	Yes
Telephone banking	Yes	Yes	Yes	Yes
Trade stocks online	Yes	No	Yes	Yes
Optional business economic checking	Yes	No	Yes	No
Maintenance fee	Yes	No	Yes	Yes
Additional checking and saving account	No	No	Yes	No
Loans and lines of credit	No	No	Yes	No
Service for cashier' check, and so on	No	No	Yes	No
Interest	No	No	Yes	No
Preferred rates on money market, CDs	No	No	Yes	No

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[5] https://www.bankofamerica.com

ent market segments based on customers' preference, balance, credit, status, and so on. Using the proposed method, we determine a platform and a set of modules for this service family. This case study focuses on a process-based platform for the family of banking services at the conceptual stage of development.

8.3.1 Phase 1: Service Process Model

8.3.1.1 Service Selection and Analysis of the Service Family

Using service analysis, we determine the service functions and service processes in this set of four services. An FPM was developed to identify relationships between service functions and processes, as shown in Table 8.3.

Table 8.3 The function-process matrix for four checking account services

Process module Functional module	Make a Deposit	Withdraw	Transfer Money	Trade Stocks	Check writing	Certify ID	Check Credit	Check Balance	Make a Loan	Open an Account	Record Transaction
Deposit	1					1					1
Withdraw		1				1		1			1
Transfer			1			1		1			1
Banking statement						1					1
Online account statement						1					1
Check writing		1			1	1		1			1
ATM transactions	1	1	1			1		1			1
Trade stocks online				1		1		1			1
Additional checking and saving account						1	1	1	1	1	1
Loans and lines of credit						1	1	1	1		1
Service for cashier' check, and so on		1			1	1	1	1			1
Online banking with bill pay			1			1		1			1
Interest						1	1	1	1		1
Preferred rates on Money Market, CDs						1	1	1	1		1
Telephone banking			1			1		1			1
Optional Business Economy Checking		1			1	1		1			1
Maintenance fee						1		1			1

8.3.1.2 Service Process Model

Based on the results of the service analysis, we can develop activity diagrams for service process modules to identify service processes or basic workflows as described in Phase 1. Through these activity diagrams we determine process features that are considered as the attributes of the service components in the checking account services. A service process model for a service function was developed from service process modules and service process components. For example, Figure 8.7 shows a service process model for a deposit service function that consists of three service process modules: (1) certify ID, (2) make a deposit, and (3) record transaction. The deposit process module is composed of three components: request, accept, and inform. Each service process component has five attributes as defined in Section 8.2.1.2.

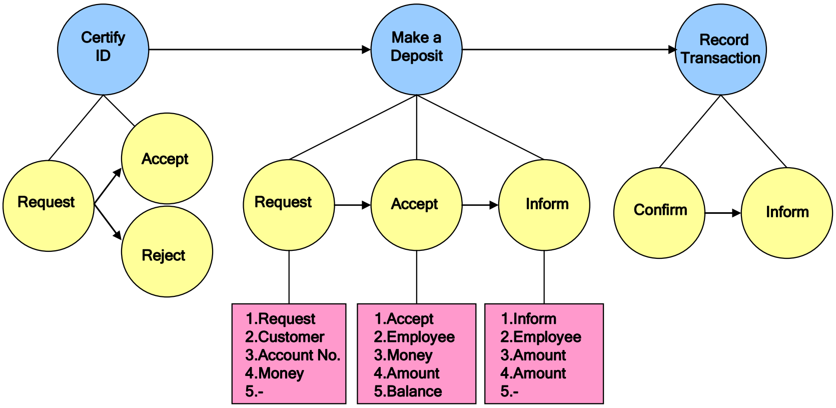

Figure 8.7 Service process model for a deposit service function

8.3.2 Phase 2: Service Ontology

The ontology for the four services was developed using Protégé[6], a graphical editing tool that has functions for developing domain ontologies, customizing the user interface, and integrating with other applications such as specific reasoning engines (Noy *et al.* 2001). Figure 8.8 shows the checking account service classes and all subclasses in Protégé. Process features in Table 8.4 are developed based on the service process analyses for the four checking account services. Each attribute takes a different code (number) related to its process feature in Table 8.4. For instance, if the attributes of a node consist of *accept* (activity), *employee* (object), *money* (input flow), *amount* (output flow), and *balance* (state), then the codes for

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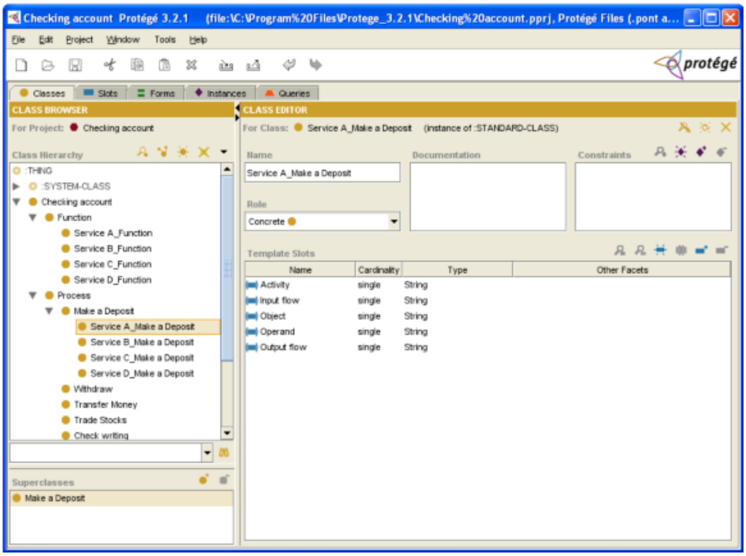
[6] http://protege.stanford.edu

the attributes are 1, 2, 4, 6, and 2, respectively. Process features' attributes are coded as shown in Table 8.4. Table 8.5 shows the 103 process features of the selected four services.



For Project: Checking account

- :THING
- :SYSTEM-CLASS
- Checking account
  - Function
    - Service A_Function
    - Service B_Function
    - Service C_Function
    - Service D_Function
  - Process
    - Make a Deposit
      - Service A_Make a Deposit
      - Service B_Make a Deposit
      - Service C_Make a Deposit
      - Service D_Make a Deposit
    - Withdraw
    - Transfer Money
    - Trade Stocks
    - Check writing

Superclasses: Make a Deposit

For Class: Service A_Make a Deposit (instance of :STANDARD-CLASS)

Name: Service A_Make a Deposit

Role: Concrete

Name	Cardinality	Type	Other Facets
Activity	single	String	
Input flow	single	String	
Object	single	String	
Operand	single	String	
Output flow	single	String	

Figure 8.8 Checking account service classes and subclasses

Table 8.4 Attribute codes for process features in the four checking account services

Code	Activity	Object	Flow (contents)	State
1	Accept	Customer	Customer ID	Credit
2	Confirm	Employee	Account no.	Balance
3	Inform	Account	Credit	
4	Query	Trading (employee)	Money	
5	Request	Balance	Employee ID	
6	Reject		Amount	
7	Proposal		Balance	
8			Message	

Table 8.5 Service representation for four checking account services

			Attributes					Attribute codes				
Service	Module Process	Component	Activity	Object	Input flow	Output flow	State	Activity	Object	Input flow	Output flow	State
Service A	Make a Deposit	$X_{1,1,1}$	Request	Customer	Account No.	Money	-	5	1	2	4	0
		$X_{1,1,2}$	Accept	Employee	Money	Amount	Balance	1	2	4	6	2
		$X_{1,1,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Withdraw	$X_{1,2,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{1,2,2}$	Accept	Employee	Amount	Money	Balance	1	2	6	4	2
		$X_{1,2,3}$	Inform	Employee	Amount	Amount	-	3	2	4	6	0
	Transfer Money	$X_{1,3,1}$	Request	Customer	Account No.	Amount	-	5	1	1	6	0
		$X_{1,3,2}$	Query	Employee	Amount	Amount	-	4	2	6	6	0
		$X_{1,3,3}$	Confirm	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{1,3,4}$	Inform	Employee	Amount	Message	-	3	2	6	8	0
	Trade Stocks	$X_{1,4,1}$	Request	Customer	Customer ID	Message	-	5	1	1	8	0
		$X_{1,4,2}$	Query	Employee	Message	Message	-	4	2	8	8	0
		$X_{1,4,3}$	Inform	Trading	Message	Message	-	3	4	8	8	0
	Check writing	$X_{1,5,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{1,5,2}$	Conform	Employee	Amount	Amount	Balance	2	2	6	6	2
		$X_{1,5,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Certify ID	$X_{1,6,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{1,6,2}$	Accept	Account	Customer ID	Account No.	-	1	3	1	2	0
		$X_{1,6,3}$	Reject	Account	Customer ID	Message	-	6	3	1	8	0
	Check Credit	$X_{1,7,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{1,7,2}$	Inform	Account	Customer ID	Credit	-	3	3	1	3	0
	Check Balance	$X_{1,8,1}$	Query	Employee	Account No.	Account No.	-	4	2	2	2	0
		$X_{1,8,2}$	Inform	Account	Account No.	Balance	-	3	3	2	3	0
	Record Transaction	$X_{1,9,1}$	Conform	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{1,9,2}$	Inform	Account	Amount	Balance	-	3	3	6	7	0
Service B	Make a Deposit	$X_{2,1,1}$	Request	Customer	Account No.	Money	-	5	1	2	4	0
		$X_{2,1,2}$	Accept	Employee	Money	Amount	Balance	1	2	4	6	2
		$X_{2,1,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Withdraw	$X_{2,2,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{2,2,2}$	Accept	Employee	Amount	Money	Balance	1	2	6	4	2
		$X_{2,2,3}$	Inform	Employee	Amount	Amount	-	3	2	4	6	0
	Transfer Money	$X_{2,3,1}$	Request	Customer	Account No.	Amount	-	5	1	1	6	0
		$X_{2,3,2}$	Query	Employee	Amount	Amount	-	4	2	6	6	0
		$X_{2,3,3}$	Confirm	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{2,3,4}$	Inform	Employee	Amount	Message	-	3	2	6	8	0
	Check writing	$X_{2,4,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{2,4,2}$	Conform	Employee	Amount	Amount	Balance	2	2	6	6	2
		$X_{2,4,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Certify ID	$X_{2,5,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{2,5,2}$	Accept	Account	Customer ID	Account No.	-	1	3	1	2	0
		$X_{2,5,3}$	Reject	Account	Customer ID	Message	-	6	3	1	8	0
	Check Credit	$X_{2,6,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{2,6,2}$	Inform	Account	Customer ID	Credit	-	3	3	1	3	0
	Check Balance	$X_{2,7,1}$	Query	Employee	Account No.	Account No.	-	4	2	2	2	0
		$X_{2,7,2}$	Inform	Database	Account No.	Balance	-	3	3	2	3	0
	Record Transaction	$X_{2,8,1}$	Conform	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{2,8,2}$	Inform	Account	Amount	Balance	-	3	3	6	7	0
Service C	Make a Deposit	$X_{3,1,1}$	Request	Customer	Account No.	Money	-	5	1	2	4	0
		$X_{3,1,2}$	Accept	Employee	Money	Amount	Balance	1	2	4	6	2
		$X_{3,1,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Withdraw	$X_{3,2,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{3,2,2}$	Accept	Employee	Amount	Money	Balance	1	2	6	4	2
		$X_{3,2,3}$	Inform	Employee	Amount	Amount	-	3	2	4	6	0
	Transfer Money	$X_{3,3,1}$	Request	Customer	Account No.	Amount	-	5	1	1	6	0
		$X_{3,3,2}$	Query	Employee	Amount	Amount	-	4	2	6	6	0
		$X_{3,3,3}$	Confirm	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{3,3,4}$	Inform	Employee	Amount	Message	-	3	2	6	8	0
	Trade Stocks	$X_{3,4,1}$	Request	Customer	Customer ID	Message	-	5	1	1	8	0
		$X_{3,4,2}$	Query	Employee	Message	Message	-	4	2	8	8	0
		$X_{3,4,3}$	Inform	Trading	Message	Message	-	3	4	8	8	0
	Check writing	$X_{3,5,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{3,5,2}$	Conform	Employee	Amount	Amount	Balance	2	2	6	6	2
		$X_{3,5,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Certify ID	$X_{3,6,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{3,6,2}$	Accept	Account	Customer ID	Account No.	-	1	3	1	2	0
		$X_{3,6,3}$	Reject	Account	Customer ID	Message	-	6	3	1	8	0
	Check Credit	$X_{3,7,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{3,7,2}$	Inform	Account	Customer ID	Credit	-	3	3	1	3	0
	Check Balance	$X_{3,8,1}$	Query	Employee	Account No.	Account No.	-	4	2	2	2	0
		$X_{3,8,2}$	Inform	Account	Account No.	Balance	-	3	3	2	3	0
	Make a Loan	$X_{3,9,1}$	Proposal	Customer	Customer ID	Amount	-	7	1	1	6	0
		$X_{3,9,2}$	Accept	Employee	Amount	Message	Balance	1	2	6	8	2
		$X_{3,9,3}$	Reject	Employee	Amount	Message	-	6	2	6	8	0
	Open an Account	$X_{3,10,1}$	Request	Customer	Customer ID	Customer ID	-	5	1	1	1	0
		$X_{3,10,2}$	Accept	Employee	Customer ID	Account No.	-	1	2	1	2	0
		$X_{3,10,3}$	Inform	Employee	Account No.	Message	-	3	2	2	8	0
	Record Transaction	$X_{3,11,1}$	Conform	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{3,11,2}$	Inform	Account	Amount	Balance	-	3	3	6	7	0
Service D	Make a Deposit	$X_{4,1,1}$	Request	Customer	Account No.	Money	-	5	1	2	4	0
		$X_{4,1,2}$	Accept	Employee	Money	Amount	Balance	1	2	4	6	2
		$X_{4,1,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Withdraw	$X_{4,2,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{4,2,2}$	Accept	Employee	Amount	Money	Balance	1	2	6	4	2
		$X_{4,2,3}$	Inform	Employee	Amount	Amount	-	3	2	4	6	0
	Transfer Money	$X_{4,3,1}$	Request	Customer	Account No.	Amount	-	5	1	1	6	0
		$X_{4,3,2}$	Query	Employee	Amount	Amount	-	4	2	6	6	0
		$X_{4,3,3}$	Confirm	Database	Amount	Amount	Balance	2	3	6	6	2
		$X_{4,3,4}$	Inform	Employee	Amount	Message	-	3	2	6	8	0
	Trade Stocks	$X_{4,4,1}$	Request	Customer	Customer ID	Message	-	5	1	1	8	0
		$X_{4,4,2}$	Query	Employee	Message	Message	-	4	2	8	8	0
		$X_{4,4,3}$	Inform	Trading	Message	Message	-	3	4	8	8	0
	Check writing	$X_{4,5,1}$	Request	Customer	Account No.	Amount	-	5	1	2	6	0
		$X_{4,5,2}$	Conform	Employee	Amount	Amount	Balance	2	2	6	6	2
		$X_{4,5,3}$	Inform	Employee	Amount	Amount	-	3	2	6	6	0
	Certify ID	$X_{4,6,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{4,6,2}$	Accept	Account	Customer ID	Account No.	-	1	3	1	2	0
		$X_{4,6,3}$	Reject	Account	Customer ID	Message	-	6	3	1	8	0
	Check Credit	$X_{4,7,1}$	Query	Employee	Customer ID	Customer ID	-	4	2	1	1	0
		$X_{4,7,2}$	Inform	Account	Customer ID	Credit	-	3	3	1	3	0
	Check Balance	$X_{4,8,1}$	Query	Employee	Account No.	Account No.	-	4	2	2	2	0
		$X_{4,8,2}$	Inform	Account	Account No.	Balance	-	3	3	2	3	0
	Record Transaction	$X_{4,9,1}$	Conform	Account	Amount	Amount	Balance	2	3	6	6	2
		$X_{4,9,2}$	Inform	Account	Amount	Balance	-	3	3	6	7	0

8.3.3 Phase 3: Module and Platform Identification

8.3.3.1 Fuzzy Clustering for Defining Modules

FCM was used to determine modules for the four checking account services. Since the number of clusters affects the number of initial modules, it is important to

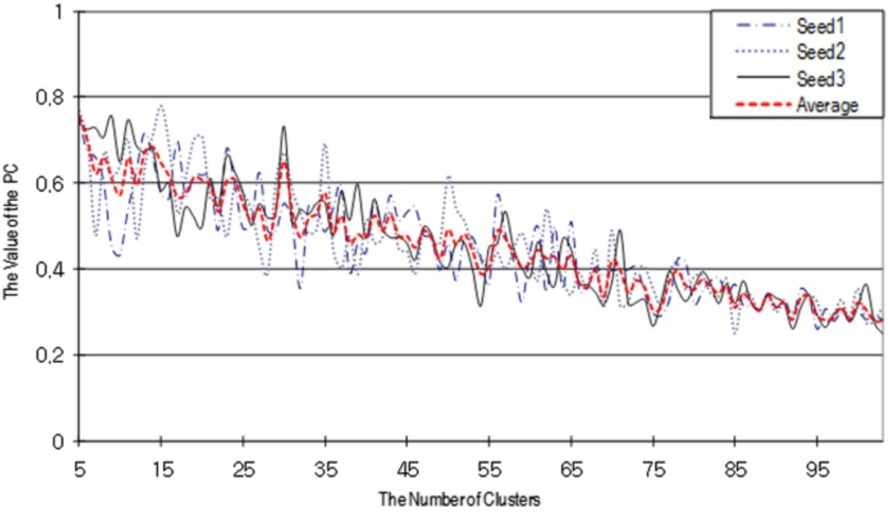


Figure 8.9 Values of the PC for three different initial seeds

Table 8.6 Clustering results for the four checking account services

Cluster	Service A	Service B	Service C	Service D
1	$X_{1,6,1}$ $X_{1,7,1}$ $X_{1,8,1}$	$X_{2,5,1}$ $X_{2,6,1}$ $X_{2,7,1}$	$X_{3,6,1}$ $X_{3,7,1}$ $X_{3,8,1}$ $X_{3,10,1}$	$X_{4,6,1}$ $X_{4,7,1}$ $X_{4,8,1}$
2	$X_{1,2,2}$ $X_{1,5,2}$ $X_{1,9,1}$	$X_{2,2,2}$ $X_{2,4,2}$ $X_{2,8,1}$	$X_{3,2,2}$ $X_{3,5,2}$ $X_{3,9,2}$ $X_{3,11,1}$	$X_{4,2,2}$ $X_{4,5,2}$ $X_{4,9,1}$
3	$X_{1,2,1}$ $X_{1,3,1}$ $X_{1,3,3}$ $X_{1,5,1}$	$X_{2,2,1}$ $X_{2,3,1}$ $X_{2,3,3}$ $X_{2,4,1}$	$X_{3,2,1}$ $X_{3,3,1}$ $X_{3,3,3}$ $X_{3,5,1}$ $X_{3,9,1}$	$X_{4,2,1}$ $X_{4,3,1}$ $X_{4,3,3}$ $X_{4,5,1}$
4	$X_{1,1,2}$	$X_{2,1,2}$	$X_{3,1,2}$	$X_{4,1,2}$
5	$X_{1,6,2}$ $X_{1,7,2}$ $X_{1,8,2}$	$X_{2,5,2}$ $X_{2,6,2}$ $X_{2,7,2}$	$X_{3,6,2}$ $X_{3,7,2}$ $X_{3,8,2}$ $X_{3,10,2}$	$X_{4,6,2}$ $X_{4,7,2}$ $X_{4,8,2}$
6	$X_{1,1,3}$ $X_{1,3,2}$ $X_{1,3,4}$ $X_{1,5,3}$ $X_{1,9,2}$	$X_{2,1,3}$ $X_{2,3,2}$ $X_{2,3,4}$ $X_{2,4,3}$ $X_{2,8,2}$	$X_{3,1,3}$ $X_{3,3,2}$ $X_{3,3,4}$ $X_{3,5,3}$ $X_{3,9,3}$ $X_{3,11,2}$	$X_{4,1,3}$ $X_{4,3,2}$ $X_{4,3,4}$ $X_{4,5,3}$ $X_{4,9,2}$
7	$X_{1,1,1}$	$X_{2,1,1}$	$X_{3,1,1}$	$X_{4,1,1}$
8	$X_{1,2,3}$	$X_{2,2,3}$	$X_{3,2,3}$ $X_{3,10,3}$	$X_{4,2,3}$
9	$X_{1,6,2}$ $X_{1,7,2}$ $X_{1,8,2}$	$X_{2,5,2}$ $X_{2,6,2}$ $X_{2,7,2}$	$X_{3,6,2}$ $X_{3,7,2}$ $X_{3,8,2}$ $X_{3,10,2}$	$X_{4,6,2}$ $X_{4,7,2}$ $X_{4,8,2}$
10	$X_{1,4,1}$ $X_{1,6,3}$	$X_{2,5,3}$	$X_{3,4,1}$ $X_{3,6,3}$	$X_{4,4,1}$ $X_{4,6,3}$
11	$X_{1,4,2}$ $X_{1,4,3}$		$X_{3,4,2}$ $X_{3,4,3}$	$X_{4,4,2}$ $X_{4,4,3}$

select the number of clusters for FCM effectively. An optimal cluster number c ($5 \le c \le 102$) was estimated by the validity index (PC) as defined in (8.4). Figure 8.9 illustrates the values of PC for three different initial seeds at fuzziness $= 1.7$ and for 10,000 iterations. In this example, $c^* = 11$ was selected as the number of clusters to determine a platform and modules for the four services, since 10 to 15 clusters provides higher average PC values than the other values. Table 8.6 shows the results of FCM using 11 clusters. Clusters that have process features for all four services can be considered as common modules.

8.3.3.2 Platform Level Determination and Result Interpretation

Using the platform level membership function described in Phase 3, the clusters' platform levels were determined as shown in Table 8.7. Since level values for Clusters 1, 3, 4, 7, and 8 indicate high platform level, these common modules can be combined into the platform for this family of four banking services.

Table 8.7 New platform and modules for the family of checking accounts

cluster	Platform level			Design
	low	middle	high	
1	0	0.2749	0.7251	Platform (Request, Query, Accept, Inform)
3	0.0039	0.1118	0.8843	
4	0	0.0114	0.9886	
7	0	0	1	
8	0.1088	0.0932	0.798	
2	0.0755	0.3711	0.5533	Module (variant and unique)
5/9	0.0903	0.9097	0	
6	0.0339	0.4048	0.5613	
10	0	0.3886	0.6114	
11	0	0.2257	0.7443	

The clusters for the suggested service platform embody a request module, a query module, an accept module, and an inform module in terms of the activities listed in Table 8.6. Therefore, the platform for the checking account services can be designed by integrating processes that are related to these activities involving a customer and an employee. Variant and unique modules can be used to increase the number of services according to customers' needs or functional requirements. The service ontology can help a designer to search for the appropriate process features related to particular service functions and processes for service design. During the conceptual stages of development, this information can provide designers with guidelines for effective service family design.

8.4 Closing Remarks and Future Work

In this chapter, we proposed a new method for identifying a service process-based platform along with variant and unique modules in a service family using object-oriented concepts, ontology, and data mining techniques. An FPM was introduced and used to identify relationships between service functions and service processes in a family of services. Object-oriented concepts were used to support service analysis and representation combining ontologies. Based on a graph model, a service process model was introduced to describe a service represented by the service ontology. Fuzzy c-means clustering was employed to cluster the process features of services based on the similarity among them and identify a service platform within the family. We demonstrated the proposed method to determine a service platform using a case study involving a family of four banking services.

The proposed method can help designers to use the newly-identified design knowledge to synthesize a platform that consists of common modules and determine a process-based platform and modules that can be adapted to service design during initial and conceptual design phase. In addition, the service design knowledge presented within an ontology can provide information and specific combinations of related modules and components based on specific constraints. It is possible that a designer can also search all of the related components in a module in service family design. Therefore, the method can help design a variety of services within a service family. Since the proposed method uses process features during clustering to determine service process modules, functional requirements for services in a family should be considered during service platform design. Future research efforts will focus on expanding the proposed method to reflect functional requirements, reusability, and configurability in platform and module design, and extending its application to various service areas and large-scale service design.

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Chapter 9
A STEP-compliant Online Product Digital Library for Customized Products

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Abstract Nowadays, small and medium-sized manufacturing enterprises (SMEs) are facing intensive competition from the global market. For these SMEs, how to better manage and record the previous product development knowledge has become a core issue for them to improve their product development process, cut down development costs, and reduce lead time. In recent years, considerable effort has been placed on developing new enabling technologies for SMEs to achieve high quality and productivity, and quickly responding to changing markets to meet customer requirements. This chapter presents our work in developing a STEP-compliant online product digital library for rapid development of high value-added customized products. The chapter focuses on how to develop the product digital library for digitizing various types of customized products. This library uses the standard for the exchange product model data (STEP) as a foundation. New methods and tools are developed to model, record, and search information such as customer requirements and expectations, engineering responses, product design, decision making, and product machining processes, *etc*. The recorded product information and knowledge in the library can be reused for the development of new customized products.

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Abbreviations

APs	Application protocols
CAD	Computer-aided design
CAPP	Computer-aided process planning
CIM	Computer integrated manufacturing
EDM	Express data model
LCP	Library of customized product
LCR	Library of customer requirements and expectations
LEV	Library of engineering voice
LMR	Library of machining resources
PDMS	Product data management system
SME	Small and medium-sized manufacturing enterprise
STEP	Standard for the exchange product modeled data

9.1 Introduction

Manufacturing markets have become more and more competitive and customer-driven in recent years. To survive and thrive in this competitive environment, manufacturing companies must utilize state-of-the-art technologies to improve all aspects of product development processes. It is essential to find globally optimized processes that can shorten the product life-cycle, reduce cost and lead time, and achieve high quality and productivity. This requires product data, information, and knowledge to be efficiently managed and utilized in a product life-cycle. As a reaction to the change in the market scenario where manufacturing is more costumer oriented, emphasis on using the Web to transfer knowledge and data within various entities of the product development cycle is increasing. The idea of integrating various users in the distributed product development process through the Web is a promising strategy for companies being forced to react to the growing individualization of demand, which has been addressed by Xie *et al.* (2003) and Li *et al.* (2004).

The main theme behind mass customization is to develop products that meet individual customer needs. This is generally closely tied to advancements in technology and its potential capabilities. The use of a product knowledgebase, which is a special kind of database to support product development, is a promising approach; however, the issues are still not fully solved in terms of how to develop an online product knowledgebase that is compatible, expandable, and able to integrate product information in various stages. There are some limitations of conventional technologies to meet the requirements of mass customization. They are (1) the *problem of integration*: conventional systems have normally been used to support the integration of one or two systems such as a computer-aided design (CAD) or the computer-aided process planning (CAPP) system. However, they cannot be directly used in the integration of the systems that are employed in other stages of product development processes such as customer interaction and engineering response to customers. (2) the *problem of cooperation:* many customized products are complex and are usually developed by combining the strength of several manufacturing companies, hence, data exchange and sharing between these companies should be very efficient and effective.

Most SMEs either do not have a product knowledgebase or structure their products using different modeling methods. Hence, it has become a challenge for them to cooperate with each other in support of the development of a particular product. Normally, an extra data conversion process should be carried out. This is very inefficient. Sometimes, conflicts about the model structures may even cause loss of information that cannot be converted. Therefore, a non-compatible system has become a barrier for collaborative development of customized products where cooperative efforts are required.

This chapter tackles the abovementioned issues and focuses on solving the following two issues: (1) how to digitally model customized products, and (2) how to take into consideration customer requirements, manufacturing constraints, supplier capabilities, and shop floor resources at the product design stage. The main objective is to develop a STEP-compliant online product digital library that can:

1. Record historical product data, information, and knowledge. The library will be used by SMEs to record their product development experiences including successes and failures, general product information, customer information, and development knowledge, *etc*.
2. Provide online tools for supporting product development processes. Online tools will be developed for users to record, search, and model various types of products. The developed library can be used as an on-line data and information library for design engineers. Evidently, through these useful tools, engineers and managers can easily and quickly source the necessary data and information.
3. Provide interfaces facilitating communications between customers and engineers. Efficient communication between a company and its customers is always important in order to develop a product quickly and meet customer requirements. The library will develop online customer interfaces for customers to interact with the company.

This chapter presents our work in developing a STEP-compliant online product digital library. First, a number of recent developments are discussed. The system architecture and a STEP-compliant product digital library are then introduced. Finally, case studies are conducted to demonstrate the feasibility and the compatibility of the proposed methods and tools.

9.2 Literature Review

STEP is currently considered a promising product modeling resource since it provides a standardized mechanism for product model data representation and exchange. Considerable research effort has been placed on how to develop STEP compliant data models, methods, and tools for supporting various product development activities. Yang *et al.* (2008) gave a comprehensive review on product modeling. Gu and Chan (1995) introduced a STEP-based generic product modeling system that was designed and implemented according to the generic resources of STEP and could thus be used to integrate manufacturing activities, such as process planning and inspection planning in the concurrent engineering environment. They presented an object-oriented approach for building product models for supporting product design. Their focus was placed on the definition of classes and the design of the user interfaces with CAD software tools. However, there were no discussions on the definition of the schemas and the knowledge modeling methodologies. Li *et al.* (1996) developed a feature-based parametric product modeling system, which employed a product model based on STEP and was managed by an object-oriented database. This system was suitable for application in a computer integrated manufacturing (CIM) environment. A STEP-based object-oriented product model based on STEP AP 224 was proposed by Usher (1996). This model was proposed for supporting CAPP analysis. A STEP-based part information model was developed for process planning purpose by Ming *et al.* (1998). Their models included a process planning information model and a production resource information model. Tang *et al.* (2001) presented a STEP-based die and product integrated information model (DPIIM), in which integrated resources of STEP were utilized to model six EXPRESS schemas. These models could support the concurrently developing stamp and die products. Zha and Du (2002) presented a product data exchange using STEP (PDES)/STEP-based assembly model for the concurrent integrated design and assembly planning.

It can be concluded that STEP has become the core of product modeling processes to organize product data in the standardized representation, which greatly enhances the capability of data exchanging and sharing in the integrated manufacturing environment. To utilize the modeling resources defined in STEP, various methods are integrated with STEP to form an integrated product modeling environment.

Application protocols (APs) are used for building up information models for the integration of STEP with different geometric modeling methods, such as AP204 addressed by ISO 2002 and AP203 addressed by ISO 1994. AP 203 integrates five types of shape representation methods that include wireframe and surface without topology, wireframe geometry with topology, manifold surfaces with topology, faceted boundary representation, and boundary representation to support the configuration controlled 3D design of mechanical parts and assemblies. For example, Shaharoun *et al.* (1998) utilized STEP to describe geometric data of a particular plastic product. The geometrical descriptions of the product were transferred into a CAD system to assist the design and machining of a suitable mold for the plastic product. Cai *et al.* (2002) proposed a method to build self-defined APs for all kinds of machine parts based on STEP. They implemented this method to develop two APs for presenting the geometric data model of the cone gear product for final driver of automobile driving axle system.

STEP also provides a suitable representation method for different features. For instance, AP224 introduced by ISO 2005 illustrates the mechanical product definition of process plans using *machining features;* AP224 and AP218 introduced by ISO 2004 also contain the STEP expressions for the specific features in the particular application areas. The entity defined in STEP can be directly utilized to represent the target features. Some self-defined features such as the special assembly structures, machining and technique information of some particular products, can be structured by using EXPRESS modeling language and integrated resources. Both STEP-defined features and self-defined features can optimize the data exchange and sharing capability of feature-based product modeling method. Typical examples of product modeling using the feature-based methods were introduced by Shah and Methew (1991), Meng *et al.* (1997), Zhao and Ma (1999), and Xie and Xu (2008).

There has been limited research work in developing STEP-based product modeling methods. For example, Chin *et al.* (2002) and Xie *et al.* (2008) proposed a multiple view methodology for integrated product modeling based on STEP. Song *et al.* (1999) utilized a STEP-based integrated product model to support the proposed design for manufacturing system. The aim was to extract the design information of parts from a CAD system for automatically evaluating the manufacturability of those parts. Jasnoch and Haas (1996) developed a collaborative working virtual prototyping environment to integrate existing CAD systems. The underlying product model of this environment was a STEP-based integrated product model.

The focus of this research is placed on modeling customized products, the definition of the knowledge structure, and the integration of the schemas with other resources defined within STEP. Schemas are defined to make sure that the proposed STEP-compliant digital library is compatible and can be used in modeling various types of customized products. These aspects, to the best of our knowledge, have not been studied extensively in literature.

9.3 System Architecture

The STEP-compliant online digital library provides input for supporting the design of customized products. The library is aimed at accumulating product development experience or knowledge for SMEs, and supporting collaborative, integrated, and concurrent product development, and capturing and responding to customer requirements. This library will be used to develop interoperability standards needed by SMEs to integrate the product design, planning, and manufacturing processes. The structure of the STEP-compliant online digital library is shown in Figure 9.1.

The library is composed of the library of customer requirements and expectations (LCR), the library of customized products (LCP), the library of engineering voice (LEV), and the library of machining resources (LMR). LCR is composed of customers' requirements and expectations and can be updated through an online customer interface. LEV records the technical attributes of a designed customer

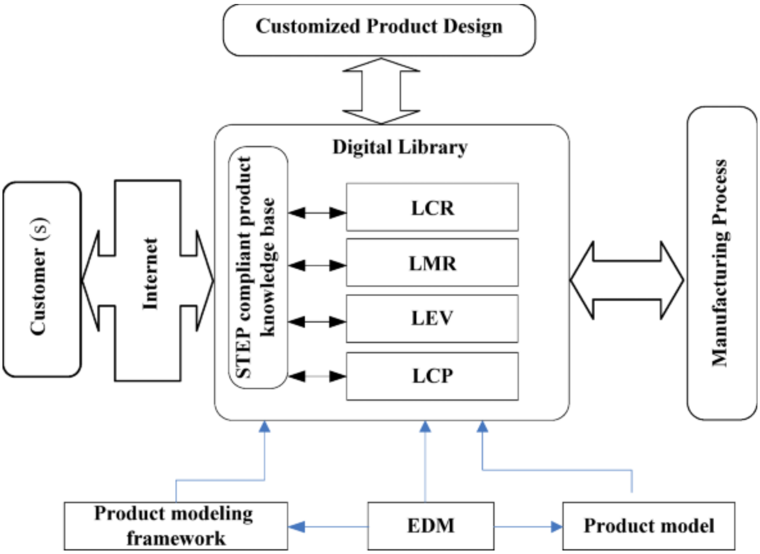


Figure 9.1 Structure of the system platform

product in response to its requirements and expectations. LMR includes the machining and manufacturing resources available in a company. LCP records all the information related to a particular customized product including geometric information, machining information, constraints, cost, lead time and knowledge, and issues related to the development of the product. The following are the basic modules and tools developed for interfacing with the library: (1) an Internet-based software platform, (2) global customer interfaces, (3) an Internet-based integrated product development environment, (4) an Internet-based product design environment for supporting product design, (5) an Internet-based virtual process planning/ assembly environment, (6) an Internet-based virtual simulation platform, (7) an Internet-based virtual manufacturing platform, (8) Internet-based design/manufacturing product data /knowledge bases and tools, and (9) a global cost estimation and optimization tool. The modules and tools were introduced in detail in previous research papers by the author (Xie *et al.* 2003, Zhou *et al.* 2007, Tu *et al.* 2007).

The product digital library is developed based on the four functional components including an EXPRESS data model, EDM, a STEP-based modeling environment, a 'five-phase' modeling method, and three EDM data exchange and sharing methods. The EXPRESS data model (EDM) is the core of the modeling framework. The EDM defines a complete product data structure and uses the standardized data format. It consists of 11 defined EXPRESS schemas and STEP AP 203, which can be found in the papers by Xie *et al.* (2008) and Zhou *et al.* (2007). Each schema utilizes either STEP resources or STEP-based compatible resources defined by our research group to model a particular type of product information.

The STEP-based modeling environment is established for the digital library. Within this environment, a modeling language-EXPRESS and its graphical representation method EXPRESS-G are used to model product structure. STEP generic resources are utilized to model product information that is defined by STEP. STEP AP 203 is used to model product geometric information and there are also new modeling resources defined for modeling product information not covered in STEP. A ‘five-phase’ modeling method is proposed to build up the EDM. It defines a formal approach to logically organize all the tasks of building up the EDM in the modeling processes (Xie *et al.* 2008).

To develop this proposed STEP-complaint online product digital library for customized products, the modeling framework and product model structure are very important. In this chapter, instead of discussing the structure and the individual modules of the entire system, the author opts to discuss the knowledgebase structure, modeling framework, product models and knowledgebase implementation of EXPRESS model, and the development of the STEP-compliant online product digital library.

9.4 STEP-compliant Product Digital Library

Figure 9.2 shows our proposed data structure of the STEP-compliant online digital library for supporting the development of customized products. The digital library is made up of the following data components: a product module, a module describing its design process, a tools module, a resources module, and an operational data and suppliers module. The product module describes the product information;,the design processes module models various design stages of the product, and the tools and the resources modules describe the information of the tools used in developing the product and resources used; supplier information related to the product is modeled in the supplier module. The relationships between these modules are represented in Figure 9.2. The proposed structure provides the basic infrastructure for digitizing customized products and is used in the author’s research group to establish the product design knowledgebase.

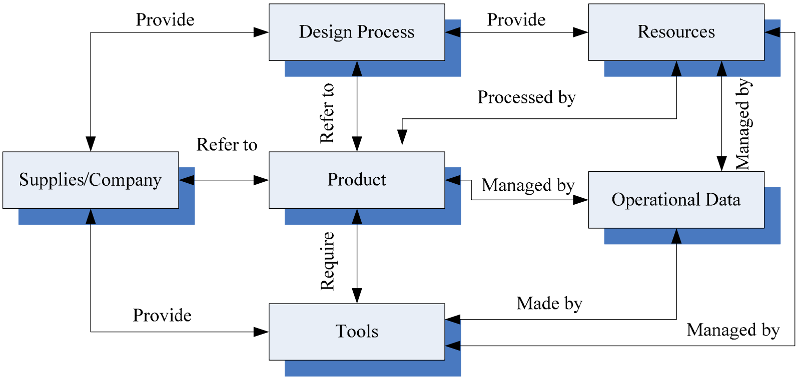


Figure 9.2 Data components in the product digital library

9.4.1 Product Knowledge Model

The product knowledge model as shown in Figure 9.3 is the conceptual description of ideas, facts, and processes that together represent the model of a customized product to be designed. The knowledge model contains four top-down information layers, which include a knowledge layer, a parts layer, a feature layer, and a parametric layer. The parametric layer contains products' geometric information. The feature layer contains all the feature information, which includes not only attributes but also relationships with other feature-level information objects and objects defined by users. The part layer contains all the part information that includes feature information and relationships among different part-level information objects. The knowledge layer contains not only parts information, but also "knowledge related" information objects and an inference engine. The knowledge in the knowledge layer is extracted from part-level knowledge and feature-level knowledge, which are formed by information objects and relationships among them. The knowledge in the knowledge layer can be directly used to support intelligent concurrent design and manufacturing. The management feature is used to manage all the information of a certain part, which can be saved and used as part of a company database. Application objects defined by users according to the requirements of the project can be put in the feature and part layer. After a new object is defined, its relationships will be created by either the users or automatically by the optimization algorithm and existing knowledge. This object with its relationships can be regarded as new knowledge, which can be used in new product design and manufacturing process.

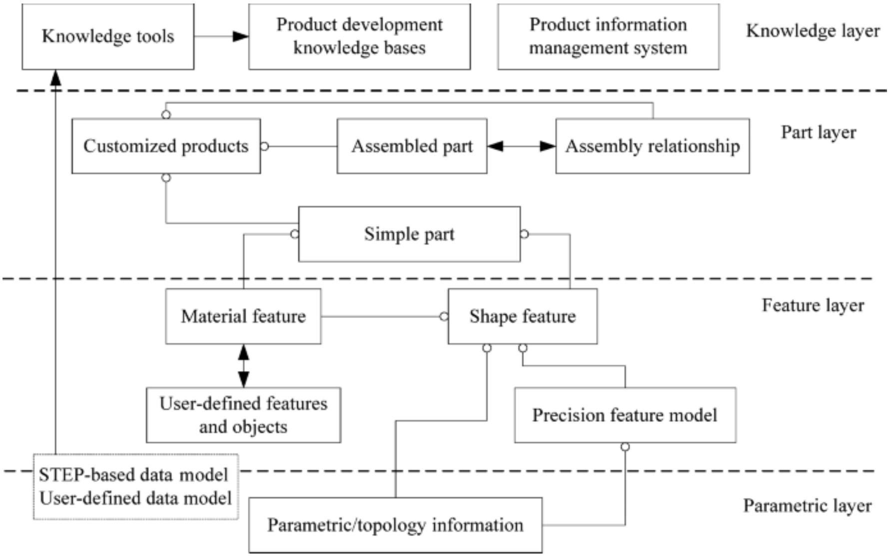


Figure 9.3 Product knowledge mode

9.4.2 Product Data Object

The object created in the product knowledge model is defined based on common concepts. There are groups of standard elements or information constructors that are used by every information model, which contain elements as follows:

1. *Entity* – construction that represents appearances from the real world.
2. *Property* – specific characteristic of entity, it could represent the numerical value, constraints, and behavior.
3. *Attribute* – certain property types setting restrictions on other properties or on whole entities.
4. *Relation* – implicit or explicit respect between two constructions in the model.
5. *Cardinality* – this defines the number of instances of one construction that can be linked with instances of the other constructions.

The entities and relations among them are the basics of the conceptual modeling. Also, the information models enclose the explicit group of the interpretation rules. The features that imply special demands on the information model are:

1. The uneven and variable structure of data.
2. The web like structure of the concept that is a result of the multiply links and dependencies.
3. The dynamic nature of data considering product development process.

The basic unit of the model is called a part. Such a part can be a piece that cannot be disassembled (called simple part) or a piece composed from two or more

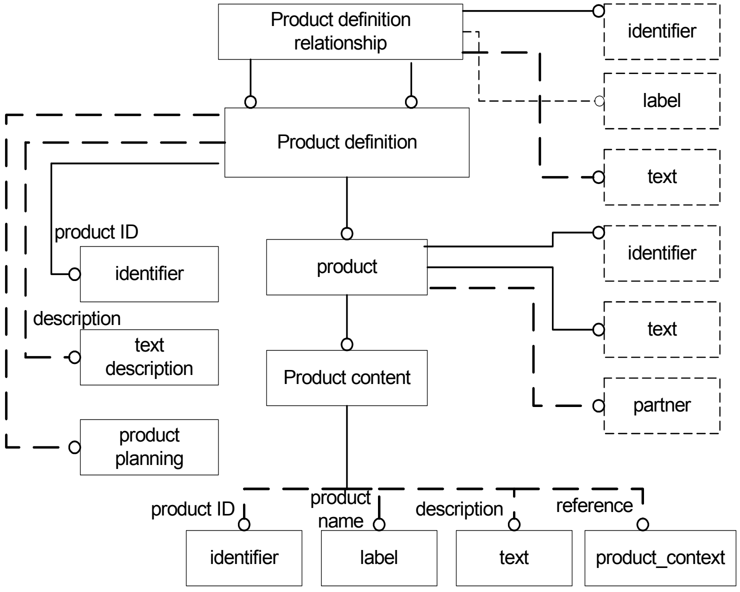


Figure 9.4 Product data description model

other pieces with defined relations between them. Four models are extracted from the product knowledge model: description model, geometric model, material definition, and feature model. The task of the description model is to define descriptive, non-geometric information about a product or assembly element. The entity product is the basic part of the description model and its purpose is to describe physical objects emerging from some process. The geometric definition of the product is the basic definition from which follows all the necessary information for analysis or product realization. The feature model is a variation of the geometric modeling, but due to the specific approach it is separated into a different model. The material definition model contains all information about materials that are necessary for the modeling or the product realization. Figure 9.4 presents a subset of entities for product structure description model using EXPRESS-G.

This model is very complex because it contains extremely large amounts of information about a product. The majority of information is stored in geometry and features models and this is the reason for simplifying the model for product structure description.

9.5 Case Study

Case studies are conducted to demonstrate the feasibility and the compatibility of the STEP-compliant online product digital library in digitalizing products from the different engineering applications. The rationality of the EDM and the relevant modeling methodologies are also tested. The clamp assembly product as shown in Figure 9.5 originated from a design project within the ENGINEERING tutorial book. Figure 9.5 shows a 3D solid model of this product, which is generated from Pro/ENGINEER® Wildfire® CAD system (Lamit 2004).

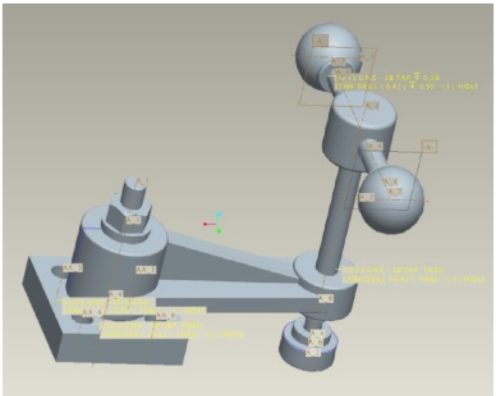


Figure 9.5 3D Model of the clamp assembly product (Zhou *et al.* 2008)

Figure 9.6 shows a tree structure model to demonstrate how this product model is assembled. The clamp assembly product consists of two subassembly components: a clamp and a plate. These two subassembly components are connected by the arm part. The subassembly clamp includes six components: an arm part, a swivel part, a foot part, a stud part, and two ball parts. The subassembly plate includes four components: an arm part, a plate part, a stud part, and a flange nut part.

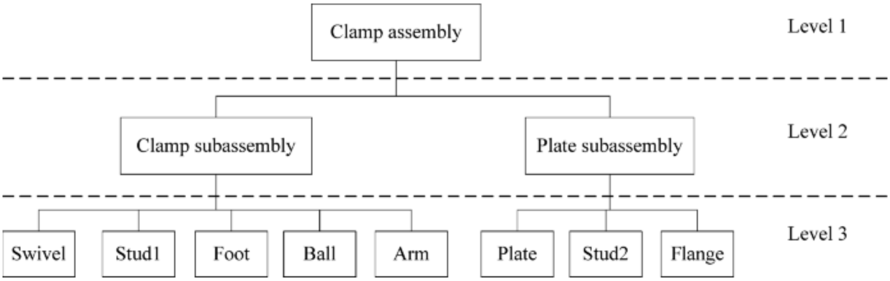


Figure 9.6 Structure of clamp assembly product (Zhou *et al.* 2008)

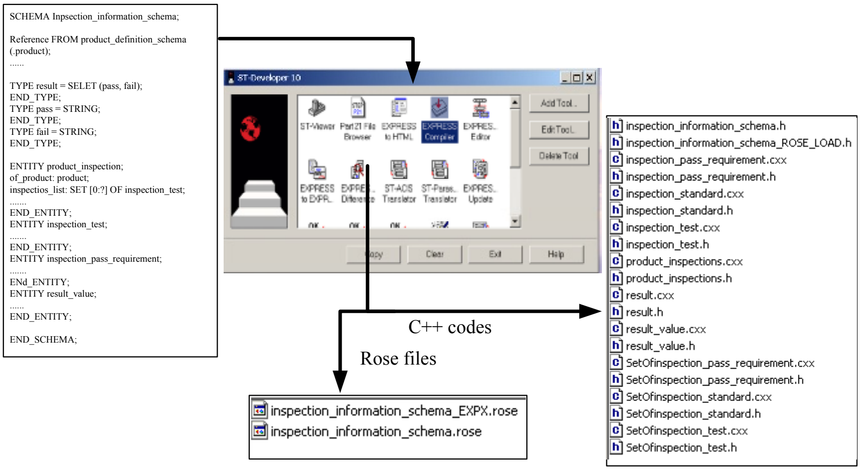
Three EDM data exchange and sharing methods, which were introduced in Xie *et al.* (2008) and Zhou *et al.*(2007) are used to model different aspects of product data of the sample product.

1. Product geometric data and product general information of the sample product are modeled into STEP Part 21 files. These two products are utilized to test product geometric data module and the *product_definition_schema*.
2. The product inspection data of the sample product are modeled as the STEP objects by an application C++ program. This is to test the *inspection_information_schema* defined in the EDM.
3. A prototype online digital library is developed to represent product data. The manufacturing processes of the assembling data of the "clamp assembly product" are modeled. They are utilized to test the *process_planning_schema* defined in the EDM.

9.5.1 Modeling Product Inspection Information

The inspection data of the product were modeled based on the working form ROSE C++ library. Through the integrated developing software environment that consists of ST-Developer and Microsoft Visual C++, the inspection data are modeled into STEP objects. This case study is carried out by following the above three steps. The product inspection information are modeled into STEP objects and presented as a STEP Part 21 file.

1. The inspection_information_schema is converted to C++ class definitions through EXPRESS Compiler in ST-Developer® as shown in Figure 9.7. Meanwhile, as the product_definition_schema and product_document_schema are referred by the inspection_information_schema, these two schemas are converted to C++ codes as well. The six corresponding ROSE schema files, inspetion_information_schema.rose, inspection_information_schema_EXPX.rose, product_definition_schema.rose,product_definition_schema_EXPX.rose, product_document_schema.rose, and product_document_schema_EXPX.rose are generated.
2. The functions and variables in these C++ codes and the data-dictionary in the *.rose files are utilized to generate the application ROSE C++ program.
3. The STEP objects are displayed in the command window and outputted in a STEP Part 21 file. The manipulations of these two STEP objects are realized by utilizing the functions ROSE.display and ROSE.saveDesign defined in the ROSE Library. Figure 9.7 presents the screen snapshot of ROSE.display( ) results.



```
SCHEMA Inpsection_information_schema;

Reference FROM product_definition_schema
(.product);
......

TYPE result = SELET (pass, fail);
END_TYPE;
TYPE pass = STRING;
END_TYPE;
TYPE fail = STRING;
END_TYPE;

ENTITY product_inspection;
of_product: product;
inspectios_list: SET [0:?] OF inspection_test;
.......
END_ENTITY;
ENTITY inspection_test;
.......
END_ENTITY;
ENTITY inspection_pass_requirement;
.......
ENd_ENTITY;
ENTITY result_value;
......
END_ENTITY;

END_SCHEMA;
```

inspection_information_schema_EXPX.rose
inspection_information_schema.rose

inspection_information_schema.h
inspection_information_schema_ROSE_LOAD.h
inspection_pass_requirement.cxx
inspection_pass_requirement.h
inspection_standard.cxx
inspection_standard.h
inspection_test.cxx
inspection_test.h
product_inspections.cxx
product_inspections.h
result.cxx
result.h
result_value.cxx
result_value.h
SetOfinspection_pass_requirement.cxx
SetOfinspection_pass_requirement.h
SetOfinspection_standard.cxx
SetOfinspection_standard.h
SetOfinspection_test.cxx
SetOfinspection_test.h

Figure 9.7 Converting inspection_information_schema into C++ classes and ROSE schema file (Zhou *et al.* 2008)

There are 19 STEP objects created in this case study, from <0–0> to <0–18>. These STEP objects are built up based on the *inspection_information_schema*, *product_definition_schema* and *product_document_schema* in the EDM.

The STEP objects <0–0> to <0–2> are the three instances of *inspection_pass_requirement* in the *inspection_information_schema*. The STEP objects <0–3> to <0–5> define three instances of the *SetOfinspection_standard*. The STEP objects <0–6> to <0–8> present the three instances of the *inspection_standard* in the *inspection_information_schema*. The STEP object <0–9> defines the product data for an instance of *document_type* in the *product_document_schema*. The STEP objects <0–10> to <0–12> present the three instances of *result_value* in the *inspection_information_schema* for three inspection tests modeled in STEP objects <0–14>, <0–15>, and <0–16>. An instance of *result* in the *inspection_information_schema* is modeled into STEP-object <0–13>.

There are three instances of *inspection_test* in the *inspection_information_schema*. For example, in the STEP object <0–14>, the *id*, *name*, and *description* are valued as “lid-inspection001” and “open torque test”, respectively. The *test_product* is valued by STEP object <0–17>, which stores the definition of the product. The *frame_of_reference* utilizes the STEP object <0–3> to define the referring standards. The other two instances *inspection_test*, STEP objects <0–15> and <0–16> are defined in the same way.

The STEP object <0–17> is an instance of *product* in *product_definition_schema*. The *of_category* utilizes STEP objects <0–18> to define the product category data about the *product* modeled in STEP object <0–17>.

9.5.2 Online Product Digital Library

A prototype online digital library named product data management system (PDMS) is developed by using the third EDM data exchange and sharing method. All product data will be stored and managed by this system. The prototype library consists of two parts: a product data interface and a product knowledgebase. These parts are both developed and based on the EDM.

9.5.2.1 Product Data Interface

This interface has two main functions. The first is to support inputting product data into the product database. The second is to manipulate product data including data querying and data updating, which is based on the support of Microsoft Access. These two functions are presented on two separated windows: data input window and data query window. Their layouts are organized according to the schemas structure of the EDM. Figure 9.8 shows four kinds of product data input windows for product general information, product inspection information, product manufacturing process information and product assembly information. A data query window is also developed to enable users to search the PDMS. The query field can be chosen from the pop-up menu. The query key word can be inputted from the blank input field and served for data query after clicking the “submit” button. The query results are presented using an excel table or form.

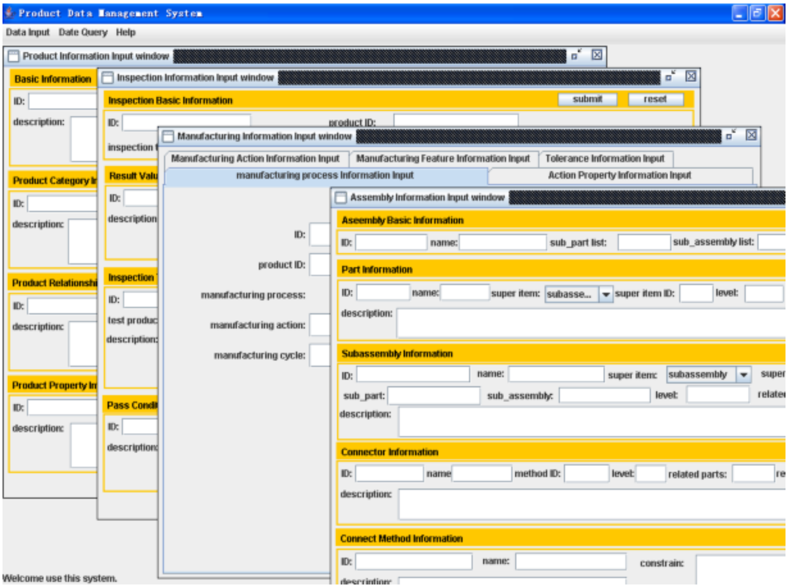
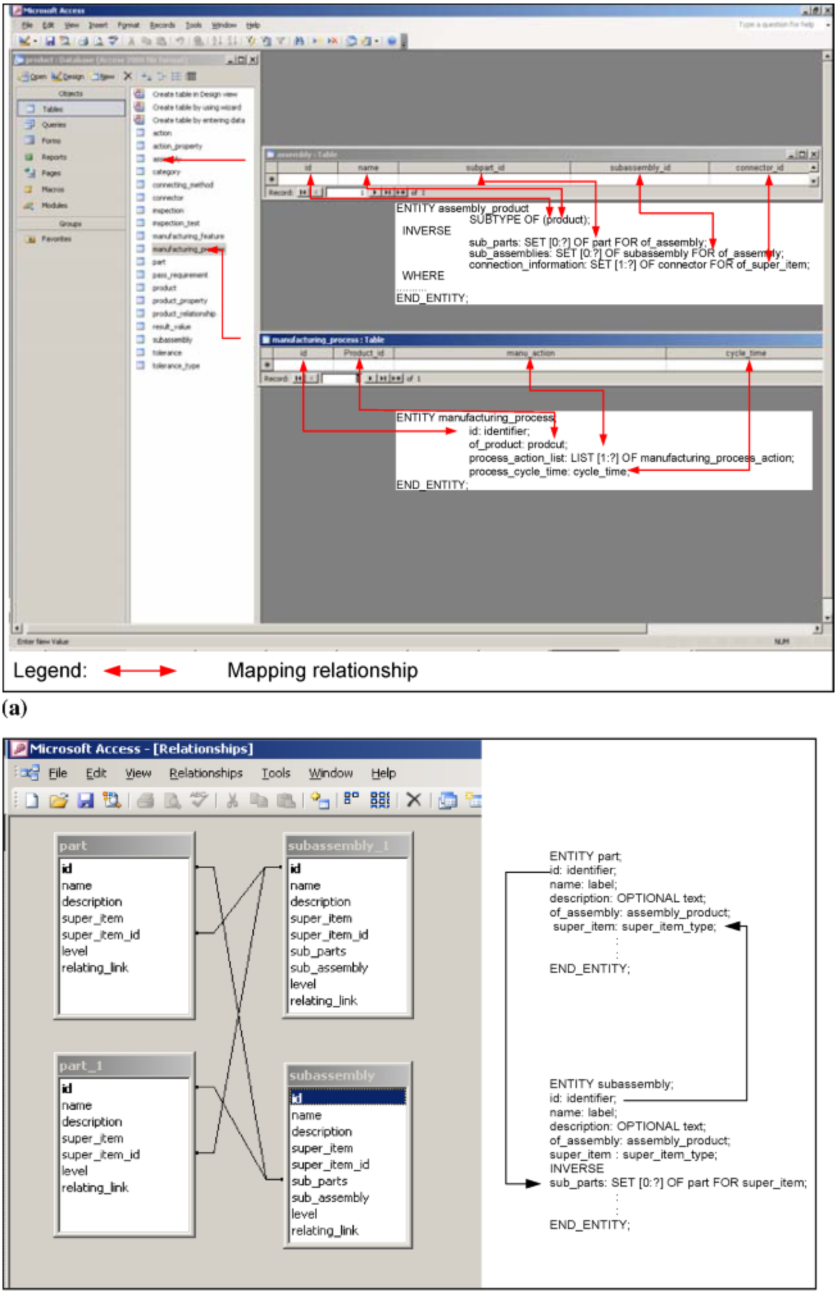


Figure 9.8 Product data input window and query window (Zhou *et al.* 2008)

9.5.2.2 STEP-compliant Product Knowledgebase

The main functions of the product database are: (1) storing the product data following the structure defined by the EDM, and (2) utilizing the Microsoft Access manipulate data. There are 19 tables in the proposed product database and they are categorized into four types: (1) the product general information, (2) the product inspection information, (3) the product assembly information, and (4) the product manufacturing process information. These tables are naturally associated with the corresponding schemas: the *product_definition_schema*, the *assembly_information_schema*, the *inspection_information_schema*, and the *manufacturing_process_schema*.

The structures of the above schemas are mapped into product database. There are two types of mappings: (1) that between EXPRESS ENTITY and the table in the product database, and (2) mapping the relationships between different EXPRESS ENTITYs to the corresponding tables in the product database. For the first kind of mapping, the attributes of an entity are mapped to the corresponding columns of a table. The name and the value type of the input field are mapped from the attribute definition. Figure 9.9a presents the first type mapping between *assembly_information_schema.assembly_proudct* and the table "assembly". The relationships between entities are also presented in between tables. Figure 9.9b shows the relationship between *assembly_information_schema.assembl_proudcty* and *assembly_information_schema.part*, which are mapped into two tables named "assembly" and "part".



```
ENTITY assembly_product
            SUBTYPE OF (product);
 INVERSE
            sub_parts: SET [0:?] OF part FOR of_assembly;
            sub_assemblies: SET [0:?] OF subassembly FOR of_assembly;
            connection_information: SET [1:?] OF connector FOR of_super_item;
 WHERE
..........
END_ENTITY;
```

```
ENTITY manufacturing_process
            id: identifier;
            of_product: prodcut;
            process_action_list: LIST [1:?] OF manufacturing_process_action;
            process_cycle_time: cycle_time;
END_ENTITY;
```

(a)

```
ENTITY part;
id: identifier;
name: label;
description: OPTIONAL text;
of_assembly: assembly_product;
 super_item: super_item_type;
                :
                :
END_ENTITY;
```

```
ENTITY subassembly;
id: identifier;
name: label;
description: OPTIONAL text;
of_assembly: assembly_product;
super_item : super_item_type;
INVERSE
sub_parts: SET [0:?] OF part FOR super_item;
                :
                :
END_ENTITY;
```

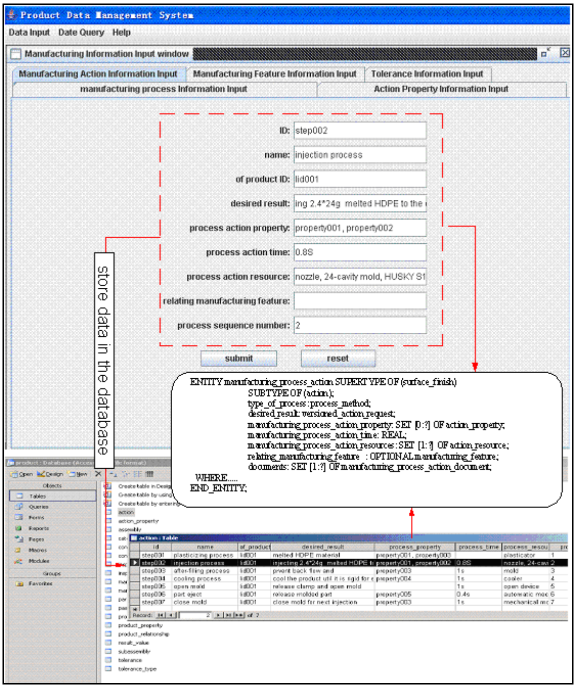
(b)

Figure 9.9 Mapping between (a) product database and (b) the EDM (Zhou *et al.* 2008)

9.5.3 Modeling Product Manufacturing Process Data

A lid is utilized to test the process_planning_schema through the prototype PDMS. This test utilizes the product manufacturing process data input interface and involves six access tables: action, action_property, manufacturing_process, manufacturing_feature, tolerance, and tolerance_type. They are built based on the process_planning_schema.

In this case study, all data of the manufacturing process of a water bottle lid are modeled. There are seven steps to manufacturing a product such as the water bottle lid. The second manufacturing step, "injection", is modeled through the PDMS shown in Figure 9.10. The product data of this step are inputted through the manufacturing action information input window (see top of Figure 9.10); they are stored in the product database table "action" (see bottom of Figure 9.10). The product data of this step are demonstrated as: (1) "step002"; (2) "injection process"; (3) "injecting 2.4*24g melted HDPE to the cavity"; (4) "property 001" and "property002", which are 210° and 840 bar, respectively; (5) 0.8 s; (6) "nozzle", "24-cavity mold", "HUSKY S160"; (7) none; and (8) 2. These eight data elements correspond to the eight attributes of manufacturing_process_action. The arrows show this mapping relationship. The product data of the other six steps are inputted into the STEP-compliant product knowledgebase as presented in the "action" table in the Figure 9.10.



ID: step002
name: injection process
of product ID: lid001
desired result: ing 2.4*24g melted HDPE to the
process action property: property001, property002
process action time: 0.8S
process action resource: nozzle, 24-cavity mold, HUSKY S1
relating manufacturing feature:
process sequence number: 2

```
ENTITY manufacturing_process_action SUPERTYPE OF (surface_finish)
            SUBTYPE OF (action);
            type_of_process :process_method;
            desired_result: versioned_action_request;
            manufacturing_process_action_property: SET [0:?] OF action_property;
            manufacturing_process_action_time: REAL;
            manufacturing_process_action_resources : SET [1:?] OF action_resource;
            relating_manufacturing_feature  : OPTIONAL manufacturing_feature;
            documents: SET [1:?] OF manufacturing_process_action_document;
  WHERE.....
END_ENTITY;
```

id	name	of_product	desired_result	process_property	process_time	process_resou	pr
step001	plasticizing process	lid001	melted HDPE material	property001, property003		plasticator	1
step002	injection process	lid001	injecting 2.4*24g melted HDPE to	property001, property002	0.8S	nozzle, 24-cavi	2
step003	after-filling process	lid001	prvent back flow and	property003	1s	mold	3
step004	cooling process	lid001	cool the product util it is rigid for e	property004	1s	cooler	4
step005	open mold	lid001	release clamp and open mold		1s	open device	5
step006	part eject	lid001	release molded part	property005	0.4s	automatic mac	6
step007	close mold	lid001	close mold for next injection	property003	1s	mechanical mc	7

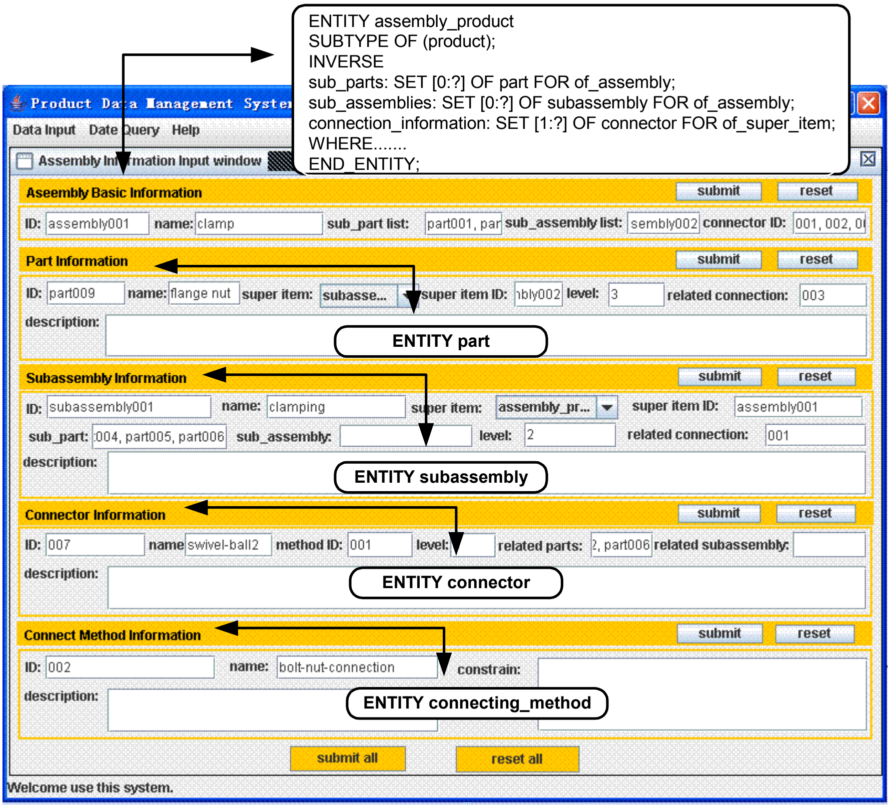
Record: 2 of 7

Figure 9.10 Modeling the "injection" step of the water bottle lid product (Zhou *et al.* 2008)

9.5.4 Modeling Product Assembly Information Data

The product assembly information of the clamp assembly product is utilized to test *assembly_information_schema* through the prototype product knowledge-base. This test utilizes the product assembly information input interface and it involves five Access tables: assembly table, part table, subassembly table, connector table ,and connecting_method table. They are built up based on the *assembly_information_schema*.

Figure 9.11 shows a user interface for inputting product assembly information. There are five fields, which are structured based on the corresponding entities in the *assembly_information_schema*. For example, the first input field named "assembly basic information" is generated by mapping the structure of the *assembly_product*. Its input "ID", "name", "sub_part_list", "sub_assembly_list" and "connector ID" refer to the five attributes of *assembly_product*: *id*, *name*, *sub_parts*, *sub_assemblies*, and *connection_information*.



```
ENTITY assembly_product
SUBTYPE OF (product);
INVERSE
sub_parts: SET [0:?] OF part FOR of_assembly;
sub_assemblies: SET [0:?] OF subassembly FOR of_assembly;
connection_information: SET [1:?] OF connector FOR of_super_item;
WHERE.......
END_ENTITY;
```

Aseembly Basic Information

ID: assembly001 name: clamp sub_part list: part001, par sub_assembly list: sembly002 connector ID: 001, 002, 0

Part Information

ID: part009 name: flange nut super item: subasse... super item ID: ıbly002 level: 3 related connection: 003

description:

Subassembly Information

ID: subassembly001 name: clamping super item: assembly_pr... super item ID: assembly001

sub_part: :004, part005, part006 sub_assembly: level: 2 related connection: 001

description:

Connector Information

ID: 007 name swivel-ball2 method ID: 001 level: related parts: 2, part006 related subassembly:

description:

Connect Method Information

ID: 002 name: bolt-nut-connection constrain:

description:

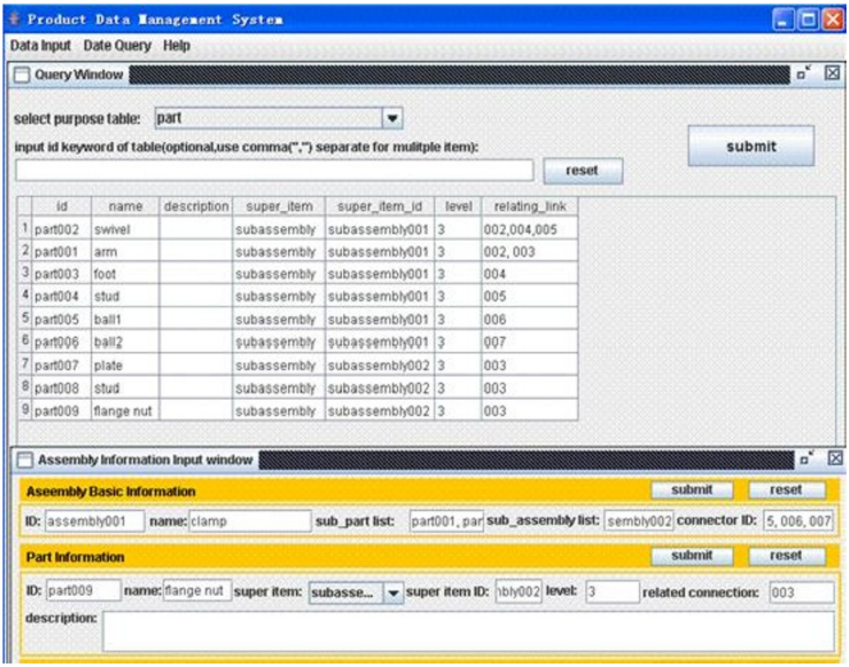
Welcome use this system.

Figure 9.11 Assembling information input (Zhou *et al.* 2008)

Figure 9.12 shows the detailed search results of nine instances of the product *clamp*. There are nine components of the clamp product. For example, as for the flange nut part, its product data are presented as: "part009", "flange nut", " ", ("subassembly", "subassembly001"), 3, and 003. They are sequentially matched to the attributes of *part*, which are *id*, *name*, *description*, *super_item*, *lever_in_assembling_hierachy*, and *connection_information*.

The product data can be retrieved from the digital library. For example, as for the "part009" shown in Figure 9.12, the "super_item" is "subassembly" and the "super_item_id" is "subassebly002". The detailed information of "subassembly002" can be retrieved by querying in the subassembly table. The "part009" is listed in the "sub_parts" column. This example presents the relationship between *subassembly* and *part*. The *super_item* attribute of *part* can be valued by an instance of *subassembly*; the *sub_parts* attribute of *subassembly* is defined by a set of instances of *part*.

Figure 9.13 shows a summary of all the assembly data about the clamp product, which are stored in the five tables (assembly, subassembly, part, connector, and connecting_method) of the product database in the prototype PDMS.



select purpose table: part

input id keyword of table(optional,use comma(",") separate for mulitple item):

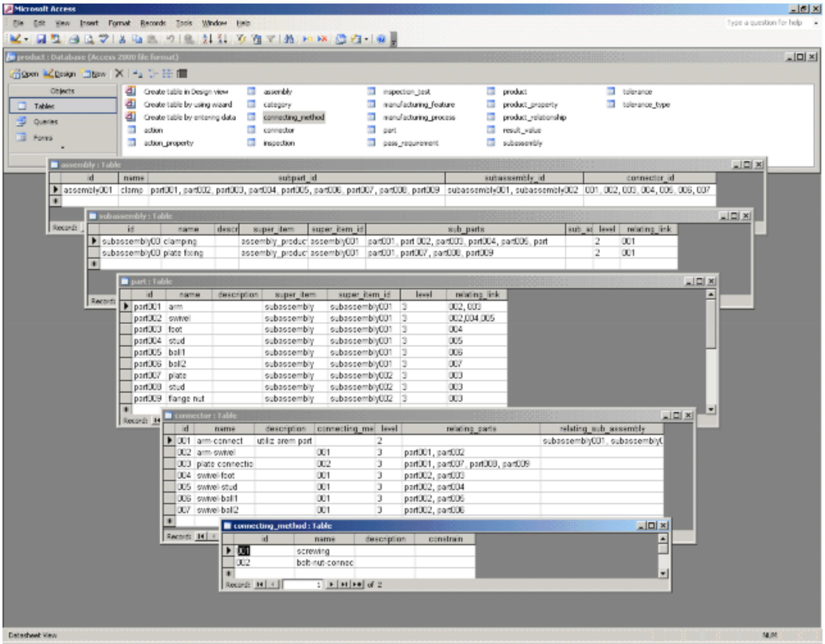
	id	name	description	super_item	super_item_id	level	relating_link
1	part002	swivel		subassembly	subassembly001	3	002,004,005
2	part001	arm		subassembly	subassembly001	3	002, 003
3	part003	foot		subassembly	subassembly001	3	004
4	part004	stud		subassembly	subassembly001	3	005
5	part005	ball1		subassembly	subassembly001	3	006
6	part006	ball2		subassembly	subassembly001	3	007
7	part007	plate		subassembly	subassembly002	3	003
8	part008	stud		subassembly	subassembly002	3	003
9	part009	flange nut		subassembly	subassembly002	3	003

ID: assembly001 name: clamp sub_part list: part001, par sub_assembly list: sembly002 connector ID: 5, 006, 007

ID: part009 name: flange nut super item: subasse... super item ID: bly002 level: 3 related connection: 003

description:

Figure 9.12 "Part" data querying results (Zhou *et al.* 2008)



assembly : Table

id	name	subpart_id	subassembly_id	connector_id
assembly001	clamp	part001, part002, part003, part004, part005, part006, part007, part008, part009	subassembly001, subassembly002	001, 002, 003, 004, 005, 006, 007

subassembly : Table

id	name	descr	super_item	super_item_id	sub_parts	sub_as	level	relating_link
subassembly00	clamping		assembly_produc	assembly001	part001, part 002, part003, part004, part005, part		2	001
subassembly00	plate fixing		assembly_produc	assembly001	part001, part007, part008, part009		2	001

part : Table

id	name	description	super_item	super_item_id	level	relating_link
part001	arm		subassembly	subassembly001	3	002, 003
part002	swivel		subassembly	subassembly001	3	002,004,005
part003	foot		subassembly	subassembly001	3	004
part004	stud		subassembly	subassembly001	3	005
part005	ball1		subassembly	subassembly001	3	006
part006	ball2		subassembly	subassembly001	3	007
part007	plate		subassembly	subassembly002	3	003
part008	stud		subassembly	subassembly002	3	003
part009	flange nut		subassembly	subassembly002	3	003

connector : Table

id	name	description	connecting_me	level	relating_parts	relating_sub_assembly
001	arm-connect	utiliz arem part		2		subassembly001, subassemblyC
002	arm-swivel		001	3	part001, part002	
003	plate connectio		002	3	part001, part007, part008, part009	
004	swivel-foot		001	3	part002, part003	
005	swivel-stud		001	3	part002, part004	
006	swivel-ball1		001	3	part002, part005	
007	swivel-ball2		001	3	part002, part006	

connecting_method : Table

id	name	description	constrain
001	screwing		
002	bolt-nut-connec		

Figure 9.13 Assembly data of clamp product stored in the PDMS (Zhou *et al.* 2008)

9.5.5 Discussion

Interfaces are designed for interacting with customers in real time within the developed prototype digital library. Through the interfaces, customers can directly input their enquiries and make changes to their requirements and expectations. The information will be fed into the company through the online system, and engineers will start a search through the digital library. The search process will check whether the company has developed similar products before. The search is carried out using a combined method involving both customer requirements (*e.g.*, keywords used) and engineer inputs (*e.g.*, feature or geometric information). If a similar product is found, its relevant information can be retrieved from the digital library, the design team can then start with this product. This greatly shortens the product development cycle and the company can respond to its customer enquiries quicker. The main advantages of developing the STEP-compliant online digital library for developing customized products can be summarized as following: (1) record of product development knowledge for reuse, (2) reduction of product development time, (3) better interaction with customers, and (4) quick response to customer changes. The STEP-compliant feature of the digital library also enables the integration of the entire product development process.

9.6 Conclusion and Future Work

This chapter presented a STEP-compliant online product digital library for rapid development of customized products. The focus of the study was to develop a STEP-compliant product knowledge base for digitizing products of different types. This is achieved through the definition of the schemas and the proposed product knowledge modeling methodologies. Case studies are carried out to validate the proposed modeling methods. A prototype online digital system has been developed to demonstrate how the library works. From the case studies, the following conclusions are drawn:

1. The proposed STEP-compliant online product digital library is compatible for digitizing products of different types. The examples from the case studies can be extended to different manufacturing applications. Through the product digitizing methods, the product data are modeled and stored in proper formats.
2. The online product digital library is able to support the modeling of a wide range of product data, especially the product manufacturing data. In the case studies, five aspects of product data are modeled through the proposed library. The corresponding product models provide a comprehensive view of the product.
3. The case studies show that all customized products are associated with the EDM. The entire product modeling processes is dependent on the data structure defined in this data model.
4. The EDM is flexible to be implemented. It has four modules. Each module of EDM, even each EXPRESS schema, can be considered as an individual EXPRESS data model. They can be applied with the EDM data exchange and sharing methods to model the corresponding product data. In three case studies, the product general information module, the product geometric data module, the *inspection_information_schema*, the *process_planning_schema*, and the *assembly_infomration_shcema* are utilized individually to support modeling product data.
5. The prototype system is developed to demonstrate how the proposed STEP-compliant online product digital library works with general database systems for modeling and managing product data. This is based on the third level of EDM data exchange and sharing method (Xie *et al.* 2008).

The STEP-compliant online product digital library provides a well established mechanism to support the integration of manufacturing systems through the proposed product modeling methodologies. However, more work needs to be carried out on developing tools for supporting the integration of product development systems. The future work in the area is enormous and not limited to the following three areas.

The first area is to further develop the prototype STEP-compliant online product digital library system. This includes the input/output interfaces for the integration of various computer aided systems, such as CAD, CAPP, and CAM. The system needs to provide a standard interface to transfer product data with proper format to the end user.

The second area is to further validate the proposed online digital library by applying it in modeling products of other types. Our research work in modeling sheet metal and injection molding products has shown that this is a complicated process (Tu and Xie 2001, Tu *et al.* 2007). Future work in this area requires great effort to define new schemas as STEP itself is still at its development stage.

The third is to explore the possibility of integrating the proposed online digital library with other Web/Internet-based manufacturing. This can enable the proposed library to be easily adopted by other Internet-based systems. The possible implementation method involves utilizing mapping between XML and EXPRESS, which is defined in STEP Part 28 by ISO (2003).

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Part III

Engineering and Management of Processes for Mass Customization

Chapter 10

Production Planning and Control for Mass Customization – A Review of Enabling Technologies

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Abstract Production planning and control (PPC) is critical to the success of mass customization (MC). It ensures production systems fulfill individual customer orders while meeting specifications, remaining within budget, and delivering on time.

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Though the objectives of PPC for MC remain the same as for conventional production, the highly diversified customer orders create new challenges: (1) difficulties in forecasting, (2) altered economies of scale, and (3) shortened lead time.

This review chapter addresses these challenges by surveying literature with relevant topics that can potentially enable MC to meet these challenges. It is concluded with an outline of research gaps and opportunities for future work.

Abbreviations

AMT	Advanced manufacturing technology
ATO	Aassemble-to-order
ATP	Available to promise
BOM	Bill of materials
BOMO	Bill of materials and operations
CPFR	Collaborative planning, forecasting, and replenishment
DBC	Design by customer
FCP	Finite capacity planning
FMC	Flexible manufacturing competence
FMS	Flexible manufacturing systems
GBOM	Generic bill of materials
IDIB	Information, decision-making, implementation, buffer
LP	Lean production
MC	Mass customization
MP	Mass production
MRP	Material requirements planning
OIP	Operational improvement practices
PPC	Production planning and control
TQM	Total quality management

10.1 Introduction

MC deals with the production of items that best serve customers preferences within their budget and lead time requirements (Tseng and Jiao 1996). This requires the combination of product customization of the one-of-a-kind production and the process efficiency of mass production (MP). To meet customers' requirements more closely translates into a new trend that companies have not been well equipped to deal with, particularly those companies that have traditionally relied on MP. Furthermore, with dynamic changes in the market place manufacturers are confronted not only with the proliferation of a wide range of products but also the pressure to fulfill customer needs within a short period of time that is much less than the traditional lead time for production. The result is a much larger decision space for companies and customers (Figure 10.1).

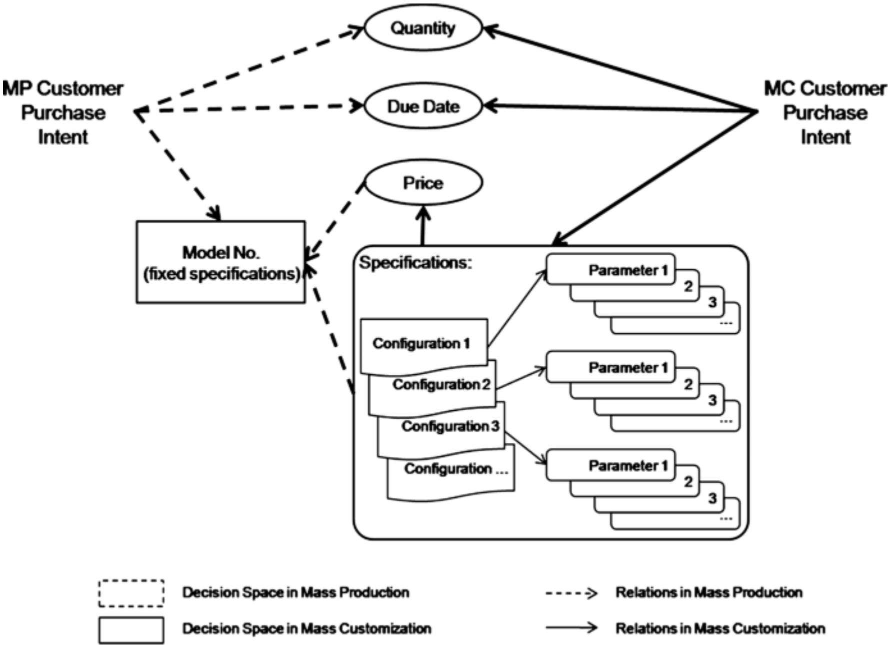

Figure 10.1 Decision space of MP *vs*. MC

Given that mass produced products tend to be commodity-like items, the order information for MP revolves around the product model number (representing a fixed set of specifications), quantity, and due date (see the left-hand side of Figure 10.1). Following the engineering approach to cost, the price is set by the marketing and sales department in advance and the product subsequently designed to accommodate cost and profit margin. Price and all other parameters can be forecasted or predicted with reasonable accuracy. However, customers increasingly demand products tailored to their individual needs. As depicted on the right-hand side of Figure 10.1, in MC product configuration replaces a fixed set of specifications. Customers order a product that incorporates their desired configuration, which is based on setting the corresponding parameters. Thus, the specification of the ordered product influences the quoted price. Due to the many different configurations, influenced by an even wider variety of parameters, the decision space inflates.

MC highly diversified customer orders create new challenges for those managing the PPC function, on three fronts: economies of scale, lead time, and forecasting. The high variety present in customer orders may considerably alter the economy of scale. Although finished products are not stocked, customers still expect lead time to delivery to be short, even shorter than the traditional lead time of MP. Because it is difficult, if not impossible, to forecast at the end product level, customers may be exposed to the full order fulfillment lead time.

To illustrate the deterioration of economies of scale induced by product variety, consider the case of car manufacturers. Currently, several automotive companies attempt to offer choices of different models with options of almost every possible attribute to the customer. The number of options is indirectly further increased by the laws and regulations in different market regions. Additionally, some adjustments need to be made to prepare the car's technology for climate. For example, markets near the equator have a hotter climate than northern regions and require the installation of additional radiators. However, also the operational environment changes: gasoline quality is superior in developed countries, road conditions less favorable in many parts or the world, *etc*. For some models the results are mind-boggling numbers of theoretical product variants. However, not all combinations are sensible and not all information needs to be queried. For example, a powerful engine with a small gas tank will hardly be recommended. The finite sets of choices could also come from compliances and rules and regulations; an order from Northern Europe, for instance, already locks in the rules regarding choices of head-lights, radio and mobile phone antenna, and engine settings to use. Thus, in practice, the actual number of options is immensely reduced.

Figure 10.2 provides a simple mathematical example of the explosion of the number of product variants for different numbers of components and different numbers of component options. Assume a case in which components can be combined without restrictions. Then the number of variants can be calculated as the number of options to the power of the number of components. That is, a product with two components and three options each can result in $3^2 = 9$ product variants. If the number of options is reduced to two there will be only $2^2 = 4$ product variants, *i.e.*, the number of product variants is reduced by $9 - 4 = 5$. For three components the product variants reduction is 19; for four components there will be 65 less product variants, and so on. Returning to the earlier example, it should be noted that for many premium car manufacturers, there is a small chance of two identical cars coming off the assembly line over the entire life cycle of each product generation.

Concerning the second challenge, long lead times, if MC production can only start after customers have placed the order and committed to the specifications, then customers have to be exposed to the entire lead time from product design, to

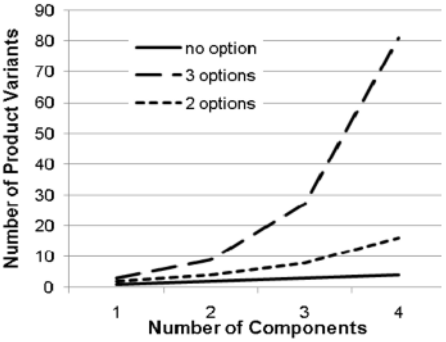

Figure 10.2 Increase of product variants based on number of components and number of component options

procurement, to manufacturing, to delivery. The vast majority, however, is not willing to wait that long. As an illustration of the significant importance of lead time on the purchase decision, in particular its trade-off potential in terms of specifications, consider the scrappage schemes that have been introduced by a number of governments in an attempt to support car manufacturers and/or providing incentives towards more fuel-efficient cars. Although a car is for many people one of the most expensive purchases in their life, potential customers not only accept massive deviations from their original specifications but even pay a considerable premium for reducing lead time. If they were not to accept these trade-offs, they might lose eligibility for the scrappage scheme as most of these are capped to a limited number of purchases.

However, the major challenge in MC is that because of the high product variety and the lead time contraction, building products to forecast is not practical to meet the diverse requirements of customers within the lead time and budget acceptable to them. Attempts to rely on ever more sophisticated enhancements of the regular MRP approach have also proven to be futile. Likewise, the existing just-in-time system cannot cope with demand fluctuations of the high-mix low-volume MC environment. This leaves companies that rely on standard approaches to PPC exposed to the challenges of MC.

Nevertheless, abandoning production planning and control altogether is not an option because it is PPC that has the most impact on realizing economies of scale and scope. PPC methodologies make the inevitable fixed costs tractable and can greatly increase efficiency. What is needed is a holistic approach to the MC production system, preparing the firm's make up for MC and providing the organization with the necessary tools to leverage economies wherever they appear.

Da Silveira *et al.* (2001) identified six success factors for MC, categorized as market-related and organization-based. On the market side customers demand for variety and customization must exist and more generally the market conditions must be appropriate. On the organization side the value chain should be ready, relevant technology must be available, the products must be customizable, and knowledge must be shared.

While the market-related factors are given in most businesses, today there seems to be uncertainty about how the organization-based factors map into enabling technologies and methodologies.

This chapter provides a review of the technologies and methodologies enabling PPC for MC production systems to achieve the seemingly conflicting goals of meeting individual requirements and achieving efficiency that is comparable to MP at the same time. The authors focus on the issues arising in the manufacturing industry. By reviewing the related literature the following questions are addressed:

1. What enablers can help overcoming the challenges posed by mass customization?
2. What features must these enablers show?
3. How can they be characterized?
4. What issues have not yet been addressed by or within these methodologies?

In order to bring the methodologies and technologies presented into a coherent framework, the authors first propose a categorization into three value chain segments versus the scope of enablers. The subsequent section presents a selection of the most relevant MC literature in each category. The conclusions section summarizes the findings and proposes some promising further research.

10.2 Enabling Framework for MC Production Planning and Control

The key idea of MC is to provide the customer with products that best fit his/her specifications, at a near MP efficiency. However, the increased variety, in addition to the cost and schedule constraints, demands a new set of production systems. Blecker and Abdelkafi (2006) proposed a sequence of strategies to manage the variety, making the system more decoupled and enabling it to cope with the variety induced complexity.

While being a first step, the focus of this sequence of strategies is on product design. However, to fully prepare the organization a holistic value chain setup is required. Having a state-of-the-art machine park and operational management practices is a necessary but not sufficient condition for success in the MC business. The customer must be provided with an interface to the company's offering that not only gives a comprehensive map of what the company offers, but is at the same time easy to use. Offering the customer to select particular options or introducing new ones into the product without already incorporating relatively easy adaptability in the product design stage will require product engineering for each new customer. This approach increases costs for the company and waiting times for the customer. However, once these steps have been successfully solved, the corporate strategy may still fail because suppliers are not responsive enough or simply unable to provide the input factors as required *by the customer*. Thus, enablers for manufacturing in MC necessarily must also include those focusing on product design, customer interaction, as well as the supply chain. Figure 10.3 provides an overview of the issues to be addressed in order to fulfill the production management.

The first block of enablers in Figure 10.3 focuses on preparing the product design for MC in a strategic scope. This includes such measures as organizing the company's entire product range according to product families. Furthermore, each product should be modularized. These two steps allow a product assembly similar to putting together a model construction kit but which eventually exhibits the customer's preferences. Supplementing these economies of scope, economies of scale can be enhanced by standardizing part components or even sub-assemblies across the different product families. This can be further enhanced by considering the commonality across different product generations. Economies of scale can be further increased by considering the commonality of production processes and grouping parts and components, accordingly.

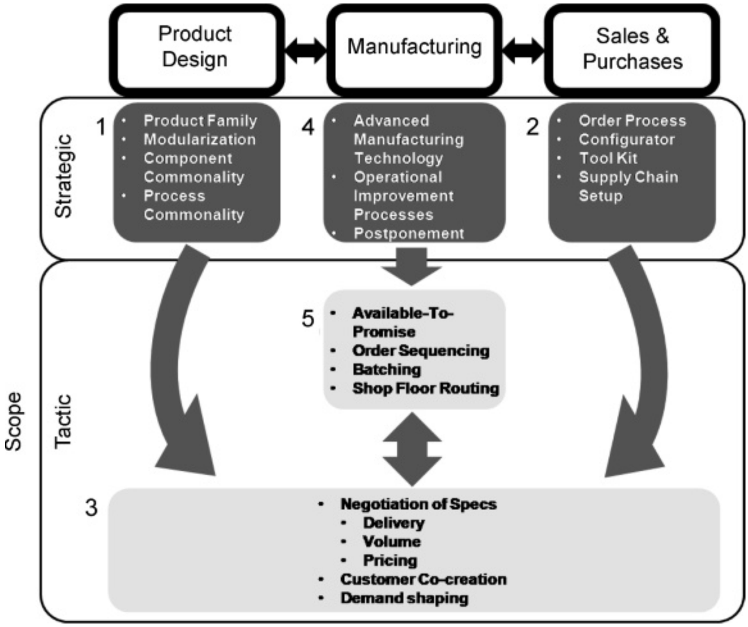

Figure 10.3 Proposed framework for the categorization of MC enablers

The second block focuses on the customer and is concerned with the strategic aspects of the sales and purchasing function. The company has to prepare its sales function by finding adequate measures for capturing customers' needs efficiently and effectively. To do so, configurations and entire "innovation toolkits" (Hippel and Katz 2002) have been proposed. Here we find the necessary approaches implemented to increase the fill-rate, in particular the demand shaping, but which are also used in the tactical side and, hence, will be described there. Using the acquired customer information on the supply side requires an adequate supply chain setup with sufficient variability and information sharing. At the end of each fulfilled project/customer order a step has to follow that identifies potentially reuseable knowledge and retains it in a knowledge base for future projects.

On the tactical level product design as well as sales and purchases both surround customer co-creation. This explains why it is difficult, if not impossible, to separate the tactical aspects of product design from those of the sales and purchases. Another focus is the company's actual negotiation of the specifications with the customer. Using the right demand shaping techniques can tremendously increase customer satisfaction by reducing the time he/she has to wait until delivery.

The manufacturing segment of the value chain and the strategic and tactical enablers will comprise the main part of this discussion.

The strategic measures of manufacturing enablers should increase the flexibility of the company's manufacturing capability. A first step is to set up and use the right machinery and equipment in the factory. This refers to the use of advanced manufacturing technology (AMT). However, to really employ the new flexibility capabilities and achieve agile manufacturing capability, companies have to implement operational improvement practices (OIP) to leverage the inherent agility in the equipment. Both AMT and OIP promise to reduce the production fixed costs seeking to make practices such as batching superfluous. Another strategic enabler is postponement. If a product can be differentiated in later production stages, without significantly increasing the value of the semi-finished product, the overall manufacturing process is more flexible to satisfy customer orders. Depending on the particular case this can be achieved by a re-evaluation sequence of the production steps. Combined with a re-evaluation of the product design itself, even later differentiation can become feasible. It should be noted that a coherent information flow between the sales side and the manufacturing center offers visibility through the production and sales pipeline, respectively. With the right tactical approaches, significant improvements in responsiveness to the customer can be gained.

The tactical scope of the manufacturing enablers is to leverage on the capabilities of the strategic measures to better serve the customers. The first element is to schedule resources in order to support the needs of different tasks. The discussion includes not only the sequencing step of the PPC, its methodology and parameterization. It also includes the role of the scheduler and the frequently neglected issue of aligning employee incentives with the employed PPC policy. The routing and batching factors not only benefit from the agility of the machine park but also from the product design that has been “optimized for MC” by using the strategic product design enablers. The available to promise (ATP) engine links the customer side to the strategic sales and purchases enablers. While some tactical sales enablers smooth the demand pattern, ATP can further balance demand and supply.

Given the vast amount of literature available towards enabling PPC for mass customization, the following review only presents the most relevant recent literature.

10.3 Enablers for Mass Customization

For this chapter we found a significant number of studies investigating the MC enablers included in the above framework. We also found other studies that have similarly explored those issues but are not directly associated to MC. We have tried to identify the most relevant sources, with the risk of missing several important works.

Furthermore, though other stages of value chain have equal or significant impacts to the smooth running of MC systems, the focus of this book chapter is on the manufacturing function. Therefore, the authors will only briefly discuss works that are focused on alternative value chain segments.

10.3.1 Strategic Enablers in Product Design

The “order penetration point” (Sharman 1984) provides an initial concept of to what extent a value chain has to react to provide for a given customer order. The goal is to reduce the impact an order has on the value chain. One way to achieve this is to design the product in a way that makes additional design or engineering efforts unnecessary for new orders.

A product family is a grouping of rather similar products in the company’s entire product range. It is often particularly interesting to introduce a product platform as a basic component that is shared among each member of the product family. A difficulty is posed by the different requirements each particular member has towards the product platform. This strategy is only feasible if it does not increase the cost of product lines. A broad review of product family design is provided by Jiao *et al.* (2007), who define the methodology and group the existing literature according to five segments. First, there are the underlying motivations for product family; then, the positioning of a company’s product offering and segmentation into product families. The design approach for platform-based product families is covered in the third group. The fourth and fifth groups address the manufacturing and upstream supply chain parts, respectively.

Employing a modular product design aims to specialize each component of the product to deliver specific functional requirements. It is thus possible to separate the design process for different components, which is particularly useful for the introduction of new technologies. Modular designs can also facilitate the standardization of components and the sharing of same component types across many different products. Kamrani and Salhieh (2000) explore different approaches to modular product design.

The effect of modularization and MC (among other issues) on the supply chain integration is studied in Mikkola and Skjott-Larsen (2004). They propose the “modularization characteristic curve” to identify opportunities for modularization and their interaction effects on interface constraints.

Another key advantage of modular designs is the opportunity to use readily available standardized parts in the product. This relieves the design and engineering function from actually designing every part of a new product and can speed up the design process at least for some products (Anderson 2003, Chapter 10).

Once the product range has been grouped into families and each product is designed on the basis of modules, major improvements can be achieved by standardizing part components and sharing their design among several different products, across product lines or even product generations. This is commonly known as component commonality. Component commonality is a concept attributable to parts, components, or sub-systems that are standardized so that they can be directly employed in different product designs, either of different products or different product generations.

In the early 1980s research began on the effects of component commonality. Collier (1982) and Baker (1985), among others, studied the effects of component commonality on safety stocks. The result was that, similar to an investment portfolio, demand risk could be pooled. Due to the overlapping of independent demand for the common component, demand fluctuations were reduced and hence a lower safety stock for the common component was sufficient in order to achieve the same service level. The more general effect of commonality on inventory costs was studied by Eynan and Rosenblatt (1996) who suggested that standardization should not always be sought. Mirchandani and Misha (2002) studied the minimization of inventory costs under given product-specific service levels and compared their results to models using aggregate service levels. Some practical advice for sourcing common components and achieving commonality ("design for manufacturability") can be found in Anderson (2003), Chapters 7 and 10, respectively.

By applying component commonality in product design to higher product hierarchies (such as modules or sub-assemblies) the deployment of tried and proven methodologies in PPC at the aggregate levels instead of end product levels is facilitated. Assuming an assemble-to-order (ATO) production system with sufficiently short assembly times (or sufficiently long customer tolerance time), PPC should shift from focusing on the many finished good variants towards the often common components. A case study followed by a simulation by Nagarur and Azeem (1999) shows that the introduction of component commonality into a production system improves its performance. A second result is the identification of the value of flexibility in manufacturing processes, which will be discussed later in this chapter. Furthermore the exploratory study of Meixell (2005) showed that, among other strategies, also component commonality may reduce scheduling problems and improve the stability of rolling schedules.

Manufacturing processes is another area that can benefit from standardization. The sources of process commonality have been investigated by Treleven and Wacker (1987). They developed metrics to measure the degree of commonality – or variety – and analyzed their managerial implications. Their study leads directly to the striving for flexible manufacturing competence, to be addressed later.

However, achieving commonality in components and processes requires the integration of both in the routing decision to benefit the company. In that direction, Jiao *et al.* (2004) propose a model to support the process selection decision based on a particular product configuration. They also describe requirements regarding the data and information flow within the company that make this integration meaningful. Huang *et al.* (2005) further integrate the decision to make or buy, offering a decision support model integrating the modularized product, processes and supply chain decisions aiming at minimizing costs. The integration of information from further domains into the decision process requires enhancements in the bill of materials (BOM).

To regain visibility over the proliferation of product and process variety, commonality (or uniqueness) of the BOM and production routings, the generic bill of materials (GBOM) was proposed. It is an approach to systematically manage product and process variety encompassing components, machinery, operations, and know-how. The integrated decision support model of Huang *et al.* (2005) employs the same approach. Jiao *et al.* (2000) propose a bill of materials and operations

(BOMO) to capture the information of material and routing in a single data structure. By doing so, they can synchronize the different perspectives of variety from the order, engineering and production planning domain. Zhang *et al.* (2005) used a GBOM to conduct a study on the organizing of product variety knowledge through GBOM. They continue the study by proposing master processes to address product variety. Du *et al.* (2005) propose an integrated BOM and routing generator for an ATO environment in order to synchronize product and process variety.

10.3.2 Strategic Enablers in Sales and Purchases

After reviewing the first step in the order process, *i.e.*, the capturing of a customer's specifications, the discussion first turns towards the steps to prepare the supply chain to deliver customized orders.

The effect of product variety on supply chain performance has been studied by Thonemann and Bradley (2002). They propose an approach to optimize the decision on how much product variety to offer. An explicitly multinational corporation point of view, characterized by considerably longer transportation links and increased demand uncertainty, is taken by Er and MacCarthy (2006)[3]. Once the effect of variety on supply chains is understood, the key idea to manage the impact of an order is to apply best practices for a high mix product supply chain in supply chain design and order taking. One such best practice is flexibility, another is close collaboration.

Although the benefits of a more flexible supply chain appear intuitive, the question of how much flexibility is needed has only recently been addressed by Tang and Tomlin (2008). The authors examined the effects of strategies to increase the agility of a supply chain by adding suppliers, engaging in flexible supply contracts, employing flexible manufacturing processes, postponing product differentiation (discussed later in this chapter), and responding to market and/or supply conditions by price adjustments. Under their assumptions, it turns out that small increases in flexibility can lead to significant reductions in the likelihood or the impact of risks, which in our case include demand uncertainty in terms of quantity, time, and product specification.

In order to facilitate the design of the supply chain when postponement (to be described later) and product modularization is pursued by a company, Ernst and Kamrad (2000) evaluate different supply chain structures by quantifying the total cost differential among them. The taxonomy they propose for the supply chain structures is rigid, postponed, modularized, and flexible, and spans upstream as well as downstream. Focusing more on the operational aspects towards and between the upstream parts of the supply chain, Schwarz (2005) proposes the "IDIB Portfolio". It supports the planning process by categorizing the decision process into four parts: the employed information system (I), the decision-making system (D), implementation systems (I), and buffer systems (B).

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[3] Er and MacCarthy (2006) also stress that forecasting remains the biggest problem in supply chain coordination.

Some authors, such as Anderson (2003, Chapter 7), suggest that forecasting should be ignored altogether. However, this will almost certainly remain an idealistic goal as not every process can be designed to offer minimal lead times. For example, some components in the semiconductor equipment industry have a production time of 6 months, yet they are needed for installation within days. Without forecasting this problem is not solvable. Thus, the question is rather how to improve forecasting instead of abolishing it, and more generally how to improve the performance of the supply chain.

The best way to do so appears to be information sharing. More general discussions about the value of information sharing are provided by Cachon and Fisher (2000), Chen *et al.* (2000), and Lee *et al.* (2000). The research of Song and Zipkin (1996) focuses more directly on sharing information about demand and inventory levels. Preparing (or supporting) the CPFR initiative are in the studies of Aviv (2001, 2002) evaluate the benefits of collaborative forecasting on the supply chain performance.

More recently, Attaran and Attaran (2007) give a brief history of CPFR and offer an overview of state of the art supply chain management systems. They also highlight that companies experiencing variation in demand, buying or selling a product periodically, and the ones offering highly differentiable products can benefit the most. The success factors for the effectiveness of collaborative planning have been surveyed and their relationship analyzed by Petersen *et al.* (2005). They conclude – as an extension to Sherman (1998) and similar to the discussion on PPC that will follow later in this chapter – that "while IT is critical […] technology cannot be the complete solution". Additionally, the right strategies and processes need to complement the technological infrastructure.

While the above literature promotes the benefits of CPFR on the supply chain performance, it assumes that all parties involved can contribute to the synergy of such a close collaboration. But this may not necessarily be the case, and so Bititci *et al.* (2007) propose a synergy model based on strategic, operational, cultural, and commercial dimensions, for which they develop a framework to assess the readiness for collaboration.

The major limitation of CPFR is the focus on the supply-side. The initiative does not explicitly include the customer side, nor extract information from it more directly. In the automotive industry this has led to the highly effective and efficient production of products that the customer does not want (Holweg and Pil 2004). More generally, for companies operating in the MC business the task is (for different reasons) even more obvious: extract information on the customer side first before feeding it through to the supply chain. Capturing such necessary customer information leads to the development of the configurator.

Capturing the customer needs by a sales person has been the standard approach and may well remain the standard in many industries. The main focus in this discussion, however, is the availability of the customer information concerning his or her product specifications that need to be entered into an order system. While this can be done by a salesperson, it can also be done by the customer if the system is good enough. Hence, the use of configurators has received wider attention in academia and industry.

A brief overview of the possibilities and promises of configurators can be found in Anderson (2003, Chapter 9, pp. 286–288). Khalid and Helander (2003) stress that the options offered by the manufacturer must be really relevant to the customer. Also, web pages soliciting customers' input must be easy to navigate, easy to use, and allow easy selection of design elements. Although every customer may have slightly different ideas about his or her product's specifications, often repetitive features are included. An (additional) tool documenting each configuration project offers the capturing of each customer's design. The more configuration projects have been realized, the broader the knowledge base, the more meaningful the potential support turns out to be. An example of such a tool is presented in Hvam and Malis (2003).

The interactions between the product nature and the available programming possibilities determine the best choice for a configurator (Anisic *et al.* 2005). The same paper gives an introductory overview of key configurator characteristics employed by leading companies. Based on the evaluation of three websites, a more thorough discussion of desirable features of a configurator, specifically for the design by customer (DBC) (Du *et al.* 2003) approach, is given in Bee and Khalid (2003).

It turns out that the customer's needs are often not readily retrievable, but rather have to be revealed. Thus, the "configuration overload" (Matzler *et al.* 2007) has received attention recently. It describes the risk that the vendor's use of the configurator demands too much product knowledge prior to the purchase. The result would be customer confusion; the customer would tend to fall back on coping strategies like sharing/delegating the decision, seeking additional information, choosing a standard configuration if available, choosing low-price offers, or – worst of all – abandoning the decision. Therefore, it is not enough just to set up a configurator; it also has to invite the customer to an enjoyable design experience, a key pre-requisite for customer co-creation.

Gathering the customer needs is, according to a generic quotation process model by Bramham *et al.* (2005) only the first in four steps to manage product variety in the quotation process. Then, a request has to be classified into whether it is an all new design and who the expert in the company is, what the extent of modifications to existing product designs are, or whether a similar product can satisfy the needs. Next, resources need to be assigned to each customer request. Finally, reusable information has to be retained if it is useful for future customers/orders. Only when all these steps are performed by an organization, is the company ready to efficiently and effectively interact with the customer in the MC environment.

10.3.3 Tactical Enablers in Product Design, Sales, and Purchases

Differentiating between tactical product design enablers and tactical sales and purchases enablers is difficult, if not impossible. They both are directly linked to the product to be produced, and thus employed in the product creation process. In essence, both act as interface between the factory floor and the customer.

A particular problem in the procurement of customized goods is the need for collaboration between customer and company in designing the most suitable product for the former, and the basically competitive nature of acquiring sales and contracting. The interdisciplinary nature of this problem has been addressed in a dissertation by Chen (2008), who developed a framework to acknowledge good design with competitive pricing. The author advocates two different negotiation schemes: the first scheme treats the customer's specifications as constraints; the second as the objective function.

MC shifts the product design process in part or entirely to the customer, offering him/her more freedom in receiving a product that incorporates his/her specifications. Such a "design by customer" approach is presented in Tseng and Du (1998). Improving communication between a MC company and its customers aims at matching the company's current capabilities with customer demands. Innovation for new design often comes from "lead users" who identify a need earlier than other customers. Supporting their innovative potential led to a stream of research on "innovation toolkits" (Hippel and Katz 2002). Hippel and Katz (2002) elaborate on the characteristics such toolkits have to offer, where they are most beneficial, how to develop them and what their competitive value is. An application of such a toolkit is presented in Franke and Hippel (2003). Recently, it has been noted that opening the one-on-one dialogue between company and customer allowing peer customers to provide information in this process is highly beneficial. The peer users can support the evaluation of a customer's self-design and even spark a product idea in the first place.

During the creation of the detailed product specifications, it may easily occur that the customer chooses a combination of options not readily available. In order to avoid delays either the salesperson or the configurator should include knowledge from the supply side. ATP offers such visibility on the supply side and will be described in the section dealing with tactical manufacturing enablers. The contribution of ATP is dependent on some degree of customer flexibility. Utilizing this flexibility to increase due date reliability and corporate revenue is the domain of the research area on demand reshaping.

The first of two main approaches is to facilitate the convergence of customers' needs and product offerings by various players of the supply chain before the purchase intention materializes. This effort can either be directed at the customer directly, as examined in Gerchak and Parlar (1987) and Balcer (1983), or indirectly towards the retailer (Taylor 2002) – assuming there is one. For MC these studies need to be extended from considering the finished good towards considering the component level, *i.e.*, the product configuration. The second approach has an on-the-spot characteristic because it is used during or after the customer made up his/her mind. It focuses on incentives like price discounts (Balakrishnan *et al.* 2005). More generally, Eynan and Fouque (2003) study the effect that changes in customer preference have before stock out occurs. Even if only a small number of customers can be convinced to alter their specification, considerable increases in profit and service level can be realized. However, they don't specify how customers are convinced to switch to a product that better suits the company's current work in process of supply chain pipeline. Merging this concept with a modularized product design may enable a company to stay closer to the original product specification because only a single component needs to be exchanged.

In computer manufacturing, for example, it is not unusual that customers demand a very popular combination of options. For many different reasons, some component may be close to stock out, *e.g.*, a hard disk. Then the manufacturer tries to make the customer accept a larger or smaller hard disk for a reduced premium or a discount, respectively.

Demand reshape practices will be addressed again later in this chapter, when the PPC aspects and the due date management in particular are covered.

10.3.4 Strategic Enablers in Manufacturing

Besides the earlier question of how much flexibility is needed to mitigate uncertainty, a key issue of operational flexibility is that customers don't necessarily perceive or benefit from a company's investment in flexible technologies and methodologies. The relationship between the so-called flexible competence (what the customer experiences) and flexible capability (the technologies and methodologies) is discussed in Zhang *et al.* (2006). Thus, this section on strategic manufacturing enablers will describe how to acquire flexible manufacturing competence (FMC), and how to increase flexibility in the production process steps by postponement. FMC is the key to reduce fixed costs in the production process and facilitate the application of tactical manufacturing enablers.

Because of the variability of customized orders in terms of time, quantity and configuration, Anderson (2003) introduces the term "on-demand supply chain" to describe a highly responsive supply chain. In Chapter 8 the author gives four main characteristics of such a supply chain: the elimination of setup, a batch size of one, one-piece flow production, and leveling production. This can be paraphrased as FMC. Yet, a remarkable feature of the discussion about FMC is that there appears to be no generally accepted definition of what it comprises. D'Souza and Williams (2000) propose taxonomy along (only) four flexibility dimensions: volume, variety, process, and material handling. The most general notion is probably that FMC strives to increase variety while reducing changeover cost and changeover time.

The experience from achieving LP suggests that FMC involves not only the use of AMT but also the implementation of OIP. An extensive overview of methods and technologies can be found in Zhang *et al.* (2006), who categorize AMT into the areas of product and process design, manufacturing, planning and control, and integration between functions and between processes. Research on AMT can be organized in groups as follows. Literature in the product and process design group supports the design and engineering activities: *e.g.*, Adler (1988), Boyer *et al.* (1996), Dahan and Hauser (2002), Huang and Mak (1999), Lei and Goldhar

(1991), and Meredith (1987). The manufacturing group encompasses literature on particular production technologies: *e.g.*, Gunasekaran and Love (1999), Kotha and Swamidass (2000), Lei and Goldhar (1991), Meredith (1987), Saraph and Sebastian (1992), and Sun (2000). The planning and control group covers literature on technologies to design and manage production activities: *e.g.*, Adler (1988), Boyer *et al.* (1996), Cunningham (1996), Lei and Goldhar (1991), Meredith (1987), and Saraph and Sebastian (1992). The technologies integrating functions and processes are described in Ettlie and Reifeis (1987), Huang and Mak (2003), Jonsson (2000), Melnyk and Narasimhan (1992), Nemetz and Fry (1988), Parthasarthy and Sethi (1992), and Small and Chen (1997).

OIP encompasses the LP concepts with the building blocks of lean manufacturing (Womack and Jones 2004), total quality management (TQM) (Crosby 1979), time-based competition (Koufteros *et al.* 1998), and continuous improvement (Bessant and Francis 1999). Concerning the relationship between AMT and OIP, the result of the study by Zhang *et al.* (2006) indicates that FMC benefits most from AMT if OIP measures are implemented.

The study by Nagarur and Azeem (1999) is mentioned here again. Like the formerly mentioned result that the introduction of component commonality improves the performance of a manufacturing system, the same is valid for the introduction of flexible manufacturing capacity. Particular benefits of commonality include reduced makespan, increased machine utilization, as well as increased factor productivity. Hence, with this increased flexibility of the manufacturing processes, batching of orders to allocate fixed costs on a production lot is no longer a dominant issue, since the economically competitive lot size is significantly reduced. Likewise the earlier mentioned study by Meixell (2005) observed a stabilizing effect of increased machine flexibility on rolling schedules by reducing system nervousness. Given the increased shop floor flexibility, the process of scheduling in a mass customization environment becomes less complex. The process itself will be addressed again in the tactical manufacturing enablers.

Postponement initiatives promise a stabilization of the demand pattern in terms of quantity and timing, because the differentiating parts of the product are required later. It is linked to the product design and allows differentiation of products late in the production process without increasing the value of the semi-finished products. As the concept of modularization is closely linked to postponement, these initiatives can involve only the product, only the process, or (ideally) both. Lee (1996) described how a production process can be changed to allow a later differentiation of a product without changing the design. He also shows the limitations of the economic feasibility of such a manufacturing postponement. Designing a product for modularity – as exemplified in Kamrani and Salhieh (2000), Chapters 2 and 3 – while keeping the goal of postponement in mind, promises wider opportunities to postpone the differentiating production steps. Furthermore, Lee (1996) introduces what is called logistics postponement. Changing the way semi-finished or finished products are distributed and further processed offers cost saving opportunities, as well. Finally, Pagh and Cooper (1998) propose a framework to decide when to strive for a strategy focusing on postponement, on speculation (*i.e.*, building up inventory), or a combination of both.

A white paper by Shen (2005) proposes a framework for developing postponement strategies. He identifies four main driving factors of postponement and outlines a process to formulate and implement a postponement strategy.

10.3.5 Tactical Manufacturing Enablers

Matching demand side with the available production capability is a fundamental issue in MC. Some rather unsubtle approaches to increase responsiveness have been identified in McLaughlin *et al.* (1994). However, as the authors note, these approaches undermine the operational system of a company by deliberately reducing visibility in general, or creating particular blind spots in the company processes. Measures to cope with such dichotomy between lead time expectation and customization are also described in McCutcheon *et al.* (1994). The rise of internet connectivity and the manifold increase in computational power since then opens new paths.

Taylor and Plenert (1999) develop a procedure called finite capacity planning (FCP) to analyze a finite capacity schedule and identify the slack machining capacity. This promises to provide better, more realistic lead time quotations, and protects the production system from over-commitment. Furthermore, by identifying unused machine capacity, sales efforts can focus on products or product configurations that use this capacity.

While FCP promises more visibility in machine utilization, demand reshaping should be employed to utilize the flexibility of customers; furthermore, information from the supply-side should be incorporated as well, to increase due date reliability and corporate revenue. ATP offers this visibility across the customer, manufacturing, and supply domain. Once the supply chain is set up to facilitate product mixes (see section on strategic sales and purchases enablers), it is essential for a competitive firm to gain visibility of its internal and external resources in the order-taking process. ATP serves as a form of integration of production and material planning (Kilger and Meyr 2008). For a discussion of different ATP execution modes and industry cases, refer to Ball *et al.* (2004).

The particular requirements towards the operations management and inventory management systems for an effective ATP system are examined in Pibernik (2005). Only if these are met can ATP contribute to customer satisfaction and corporate success. Xiong *et al.* (2003) present a web-based ATP system with the key feature that it promises to respond faster to customer queries. This is achieved by an open-source architecture and the use of a dynamic bill of materials (dynamic BOM), which make the consideration of component and raw material availability less computationally expensive. Thus, the WebATP promises) to become a feasible scenario planning tool.

A planning model integrating information from supply and demand side for the order commitment process is presented in Zhang and Tseng (2008). This model explicitly and coherently considers the flexibility of the manufacturing system and customer's flexibility regarding his/her specifications, which have both been addressed in earlier sections of this chapter.

A brief discussion of a single-level or two-level hierarchy approach to the scheduling process, the model building, and potential problems when choosing the size of time buckets is presented in Stadtler (2008). Choosing the wrong time bucket size may lead to scheduling excess idle capacity even if a job barely exceeds the remaining capacity of a time bucket. The author also mentions approaches to remedy this problem.

Hutchison and Khumawala (1990) in particular addressed the scheduling of flexible manufacturing systems (FMS). They compare the output and flow time results of real-time and off-line scheduling schemes. They conclude that the off-line scheme yields better performance for little additional computational effort. However, the insights might be outdated because the computational power has increased by several orders of magnitude since the early 1990s.

A literature review on due date management policies is given by Keskinocak and Tayur (2004). They note that lead time reliability/due date reliability is among the most important factors influencing service quality. The effect a due date quotation has on the customer is addressed in Moodie and Bobrowski (1999). They consider trade-offs between price and promised due date with the result that in a simplified setting bargaining over price and due date is beneficial to the company.

This leads to the observation that there is no single best practice of PPC methodology, neither for all manufacturing systems nor all products within the same company. A brief discussion of the aids supporting selection of methods for PPC is presented in Schönsleben (2008). Schönsleben and Wiendahl (2009) introduced the strategic and tactical implications of market changes to production. These, of course, not only involve the facility layout, the machinery and equipment, including AMT, but also the supporting processes OIP. For a thorough discussion of this problem with extended scope towards facility location planning for production, distribution, and service networks as well as strategic procurement, see Schönsleben (2007).

Based on a control theoretic approach, Kim and Duffie (2004) design and analyze closed-loop PPC algorithms for a single workstation. Their results support the implementation of FMC to be able to adjust capacity more often and with less delay. They argue that more responsive capacity control has greater impact on production performance than more sophisticated backlog control algorithms.

A PPC model establishing a relationship between production planning, control, and production performance metrics is presented in detail by Lödding (2008). Based on this model, Nyhuis *et al.* (2009) develop a model founded on control theory. The closed control loop setting allows a constant measuring and steering of production systems. They also present an approach supporting the customization and parameterization of a PPC system for individual companies and their particular production characteristics.

Having discussed the technical side of scheduling, which often focuses entirely on the sequencing, soft factors of scheduling, such as social and organizational aspects, will be introduced in the following.

Wiendahl *et al.* (2005) argue that problems in the PPC configuration are easily recognized but that a technology centered approach cannot solve them. Instead, they demand an approach including the agents and their roles. In their study they identify six aspects for a successful implementation of a scheduling strategy: objectives, processes, objects, functions, responsibilities, and tools. The authors also propose a checklist for decision-makers to use in order to ensure that the PPC system is consistently configured and aligned. In Wiendahl (2008) the approach is discussed in greater detail and supplemented by an industry case.

It should be noted that the functions and responsibilities of schedulers have not been addressed yet. To deepen the understanding of the tasks and roles of schedulers in particular, we refer to Jackson *et al.* (2004). Their study emphasizes the need to take a more holistic approach to scheduling.

Sequencing and scheduling for MC is thus not only limited to using the right models and parameters, but it must also address the role schedulers will have to play. Often, the sequencing part is done entirely by algorithms and computers. Schedulers double-check the generated plans for consistency and also play a major role in foreseeing interruptions in production and develop contingency measures.

The diminishing importance of batching has been addressed in earlier sections, particularly in the context of commonality and FMC. While the former increases the number of copies for a particular component to be produced, the latter *de facto* reduces the economic lot size by reducing the fix cost and set up times.

Similarly, sequencing is facilitated by enablers in other domains. Increasing the process commonality opens more routings for a particular production step. FMC promises to reduce the influence of the production sequence on changeover cost.

Finally, it should be noted that the scope of the term PPC is broadening since the coining of a generally accepted term in the 1970s. Today, it not only involves the internal material management but extends across the firm boundaries to include the entire value chain from the first supplier to the final customer. Schuh *et al.* (2008) noted that the vertical and horizontal integration of relevant information remains a challenge.

10.4 Conclusion

Differing from MP, mass customization encounters the challenges of producing to meet customers' orders with vast product variety and lead time limitation. These challenges translate into operation management in PPC for MC with difficulties in demand forecasting, altered economies of scale, and expectations of shortened delivery lead time. Thus, the requirements of mass customization can best be met by better aligning economies of scale and scope of the entire supply chain, and the product development process. This process may involve the following practices:

1. Appling modularization and commonality in product and process design to higher product hierarchies (such as modules or sub-assemblies) so that tried and proof methodologies in PPC can be deployed at the aggregate levels instead of end product levels.
2. Involving the customer in product design and innovation by using configurators and toolkits, and taking into account the flexibility of the customer by shaping his or her specifications.
3. Creating a coherent process to align the partnership of product design with the competitiveness of order acquisitions and apply best practices in high mix product supply chain to ensure uninterrupted information flow of customer generated demand through the entire value chain from the customer through the manufacturing supply chain and to the delivery supply chain.
4. Preparing the shop floor for the increased variability of demand by using AMT and implementing OIP in order to make manufacturing fixed cost irrelevant. Striving for postponement to create a higher degree of responsiveness to customers' demand by delaying differentiating production steps.
5. Gaining visibility over the upstream value chain to match demand and supply by using ATP, and aligning the order sequencing approach with the organizational setup.

This proposed framework is an attempt to conceptualize the different enabling approaches to PPC in MC from the literature, from which further work can be identified. One possible research direction concerns the parameterization of the enablers. There exist several categorizations for MC along different dimensions, *e.g.*, Gilmore and Pine (1997), Lampel and Mintzberg (1996), and McCarthy *et al.* (2003) to name but a few, and it is likely that different MC categories require different enablers. Hence, further research is required on the effect the degree of customization has on the enablers described in this chapter. Some enablers may not be required; others may have to be adjusted. Also, MC still offers a fertile area for empirical studies to support this framework and other works.

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Chapter 11

Designing and Planning of Material Handling Systems for Mass Customization

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Abstract Mass customization (MC) involves the challenge of high product proliferation and frequent production volumes change. Flexible manufacturing has been treated as the main solution for these challenges. However, without a flexible material handling system (MHS), flexible manufacturing cannot be implemented successfully. Therefore, the designing and planning of the flexible MHS has attracted intensive research. This chapter first reviews different types of MHS in MC. In order to evaluate the performance of MHS, qualitative and quantitative measures are proposed. Then a detailed designing and planning of a flexible MHS using free-ranging automated guided vehicle (AGV) with an indoor local position-

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ing system (LPS) is illustrated. As a case study, the layout of the proposed flexible MHS in the apparel industry is designed. Then to assess the effectiveness of the proposed flexible MHS, Monte Carlo simulation and analytical models are formulated to compare its operational performance with that of the fixed-track systems commonly used in the apparel industry. Economic feasibility analysis is also included. Based on our analysis, the proposed flexible MHS has potential advantages over the fixed-track system in an MC environment.

Abbreviations

AGV	Automated guided vehicle
AS/RS	Automated storage/retrieval systems
ATCF	After-tax cash flow
AVT	Average time in the system
BTCF	Before-tax cash flow
CT	Cycle time
CV	Coefficient of variation
FIFO	First in first out
FRAGV	Free-ranging automated guided vehicle
IRR	Internal rate of return
J-Eton	Joined Eton
LPS	Local positioning system
LWS	Length of the workstation
MACRS	Modified accelerated cost recovery system
MARR	Minimum attractive rate of return
MC	Mass customization
MCE	Manufacturing cycle efficiency
MHS	Material handling system
PWC	Practical worst case
RFID	Radio frequency identification
SJ-Eton	Simply joined Eton
TH	Throughput quantity
TSS	Toyota System-Style
TTD	Total transportation distance
UK	United Kingdom
UPS	Unit production system
USB	Universal serial bus
VAE	Value added efficiency
WIP	Work in process

11.1 Introduction

MC has made considerable inroad in a number of industries such as the hospitality industry, the information industry, and particularly the manufacturing industry (Silveira *et al.* 2001). The net result of MC has significantly increased the variety of products and the frequency of changing volumes of demands. This proliferation of variety has put substantial stress on the manufacturing system in terms of the ability to flexibly and rapidly respond to customer demands. Therefore, to realize mass customization, the flexible manufacturing system has to be deployed (Bock and Rosenberg 2000, Chakraborthy and Banik 2006, Cheung 2005, Xiao *et al.* 2001). As one of the critical components of flexible manufacturing systems, the flexible material handling system plays a strategic role in the implementation of flexible manufacturing systems (Beamon 1998, Jawahar *et al.* 1998). According to Sule (1994) and Tompkins *et al.* (2002), material handling accounts for 30–75% of the total cost of a product, and efficient material handling can be responsible for reducing the manufacturing system operations cost by 15–30%. However, inadequately designed MHS can indeed interfere severely with the overall performance of the production system, and lead to substantial losses in productivity and competitiveness, and to unacceptably long lead times (Chakraborthy *et al.* 2006). This makes the subject of material handling increasingly important. In addition, all the complexity of manufacturing is passed on to the material handling system. Therefore, the designing and planning of the flexible material handling system is considered as an important issue in production planning and control in MC.

There are many material handling systems in the real world. Each system has its own pros and cons for particular applications. Therefore it is crucial to select the proper type of material handling systems for MC. For instance, with the advent of barcode and radio frequency identification (RFID), material movement can be tracked effectively and automatically. As a consequence, it makes sense for MHS supporting MC to be moving towards automation. To carry out the designing and planning of flexible material handling systems, several quantitative performance measurements are needed to guide the designing process. At the same time they can also be used to verify the performance of the entire production system for MC in the case study. In this chapter, first in Section 11.2, we will show different kinds of MHS which can support MC. The pros and cons of these systems are discussed to select the proper type of MHS for MC. Several qualitative and quantitative performance measurements are also provided to guide the designing process. Then the detailed designing and planning of a flexible MHS using free-ranging AGV with an indoor LPS is illustrated. In Section 11.3, as a case study, the application of existing automatic MHS for an apparel manufacturer is discussed. To assess the effectiveness of the proposed flexible MHS, its performance is compared with that of a fixed-track system such as the Eton System already implemented successfully in the apparel industry. An analysis showing the potential advantages of free-ranging MHS over the fixed-track MHS will be presented. Finally, recommendations and conclusions are presented in Section 11.4.

11.2 Designing and Planning Considerations on Material Handling Systems for Mass Customization

To identify the proper MHS for MC, different flexible MHSs are reviewed and compared using qualitative analysis. We find that the free-ranging MHS has potential advantages for MC. To clarify the potential advantage, quantitative analysis is necessary. Therefore, several performance measures of flexible manufacturing are proposed. Finally, detailed designing and planning considerations of a flexible MHS using free ranging automated guided vehicle with an indoor LPS are illustrated.

11.2.1 Different Flexible Material Handling Systems

Generally, the determinant of a material handling system involves both the selection of material handling equipments and the assignment of material handling operations to each individual piece of equipment (Sujono 2007). Moreover, the scheme of the assignment highly depends on the material handling equipment. Hence, we can classify material handling systems mainly by the type of the material handling equipment.

In the literature, material handling equipments are classified into main groups of industrial trucks, conveyors (*e.g.*, Figure 11.1), fixed-track automated guided vehicles (*e.g.*, Figure 11.2), cranes, industrial robots, and automated storage/retrieval systems (AS/RS) (Kim and Eom 1997). Actually, manual material handling is still fairly popular in many industries such as the electronics manufacturing industry and the apparel industry. Since manual material handling, industrial trucks, and cranes involve human beings, we can group them together as the manual-type MHS. The industrial robots and automated storage/retrieval systems operate with a fixed position. Therefore, they are classified as fixed-point MHS. Recently artificial intelligence has been applied to material handling. The conceptual free-ranging AGV MHS was proposed in (Dai *et al.* 2008). Other classes of MHS are presented in Table 11.1.

Table 11.1 Summary of material handling systems

System type	Examples
Manual-type MHS	Manual handling, industrial trucks, cranes
Conveyor MHS	Conveyor belt, roller conveyor
Fixed-point MHS	Industrial robots, AR/RS
Fixed-track AGV MHS	Lift AGV, tugged AGV
Free-ranging AGV MHS	Free-ranging MHS

Figure 11.1 Conveyor belt of conveyor MHS

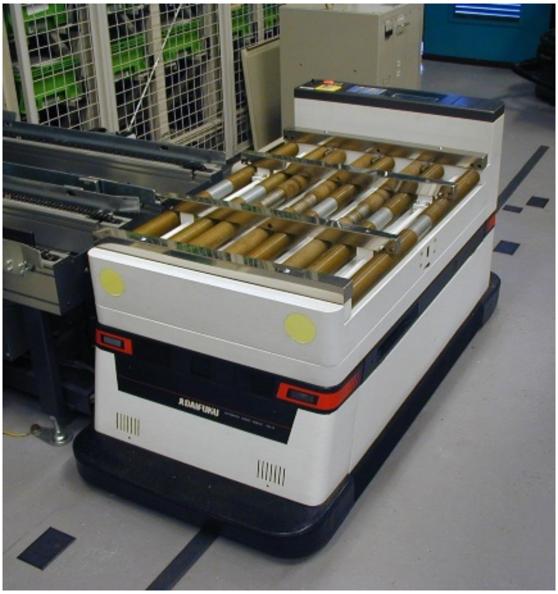

Figure 11.2 Fixed-track AGV MHS

11.2.2 The Designing and Planning of Flexible Material Handling Systems

After reviewing the flexible MHS, it is interesting to select and design the proper MHS for MC. Evaluation can then be conducted according to the proposed performance measures.

11.2.2.1 Qualitative Performance Comparison of Material Handling Systems

There is much literature focusing on the evaluation and selection of material handling systems (Fonseca *et al.* 2004, Rao 2006, Rembold and Tanchoco 1994). Different models have been formulated to compare the performance of material handling systems. In them, MHS are classified according to the flexibility and speed they provided to the production system. Such classification is presented in Figure 11.3. Their performances in setup cost, operating cost, quality, and reliability are presented as well. When the handling process becomes complicated, manual MHS is easy to make mistakes, and therefore the process reliability will be low. Moreover, in the manual MHS, materials are handled by bundle, and it may be easy to cause material defects. As a consequence, the product quality will be affected.

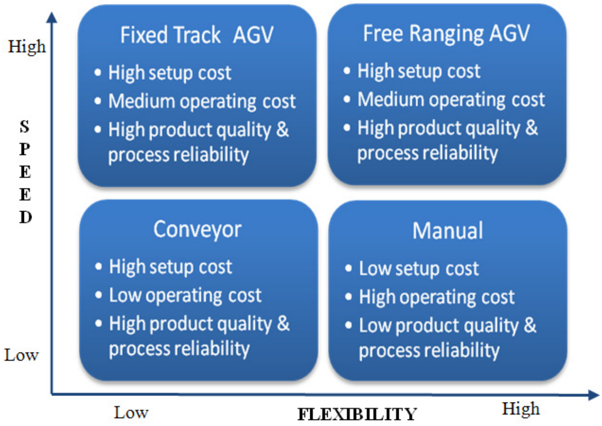

Figure 11.3 Summarized comparisons of the MHS

11.2.2.2 Performance Measures

Manufacturing system effectiveness is a function of manufacturing cycle efficiency, value added efficiency, work in process, average time in the system, and through-put quantity. These are classical performance measures of MHS. Workstation utilization and the total transportation distance can sufficiently explain the underlying reasons for the improvement of MHS. Hence they are also included as efficiency determinant factors, and presented in the following terms.

Manufacturing Cycle Efficiency (MCE)

MCE is a traditional measure of the manufacturing process. It is defined as the ratio of the time in actual production and setup process over the total time in the production area (Fogarty 1992). The higher the ratio, the higher the percentage of time spent in the workstations. The definition is shown in the following formula.

$$MCE = \frac{S+R}{S+R+W+M} \tag{11.1}$$

Where S denotes the total setup time, R denotes the total running time, W denotes the total waiting time, and M denotes the total material handling time.

Value Added Efficiency (VAE)

VAE measures the percentage of time added to a product during the production process. It is defined as the ratio of total run time to the total manufacturing time (Fogarty 1992) as shown in the following formula:

$$VAE = \frac{R}{S+R+W+M} \tag{11.2}$$

Although VAE looks similar to MCE, when the setup time is relatively large, improving MCE not always leads to significant productivity improvement. Therefore, VAE is valuable when measuring the performance of the manufacturing system, particularly the system whose setup time is changed.

Work In Process (WIP)

WIP is defined as the inventory between the start and end points of a product routing, and it is commonly used as a criteria to assess manufacturing systems (Fogarty 1992, Viswanadhamand Narahari 1992). It has significant effect on the inventory cost and the capability of flexibly and quickly responds to customers requirements.

Average Time in the System (AVT)

AVT is the long-term average time of a part spent in the system from entering the loading station to departing the unloading station. This can be used to measure the speed of the response to a new order (Sameh and Mike 1998).

Throughput Quantity (TH)

TH is often simply referred to as throughput or production volume and it is the number of jobs completed in a given period of time. This may also be denoted by production rate (Beamon 1998; Egbelu and Tanchoco 1984). According to Littles' law, the relationship between TH, WIP, and the cycle time CT is defined as:

$$TH = \frac{WIP}{CT} \tag{11.3}$$

When comparing the performance of manufacturing systems, we often need to consider the performance in the practical worst case. The TH of the practical worst case TH_{PWC} of given WIP level w is defined as follows (Tompkins *et al.* 2002):

$$TH_{PWC} = \frac{w}{W_0 + w - 1} r_b \tag{11.4}$$

$$W_0 = r_b T_0 \tag{11.5}$$

Where W_0 denotes the critical work in process, r_b denotes the bottleneck rate, and T_0 denotes the raw process time.

Workstation Utilization

Workstation utilization is defined as the fraction of actual operating time to the total available time (Viswanadham and Narahari 1992). It reflects the average efficiency of the workstations being used in the production line. In the apparel industry, the order size is relatively small. Different products often require different sequences of production processes. Due to the fixed-track property of Eton Systems, it is necessary to change the locations of the machine to suit a new product. Relocating machines takes time. Therefore, it would decrease the productivity of the entire system. However, since the free-ranging AGV (FRAGV) has the property of free path, there is no need to relocate the workstation for launching a new order.

Here, we assume that all these workstations are never idle and never fail before finishing an order. Furthermore, the production line is well balanced. As we want to compare the performance of the free-ranging MHS and fixed-track systems, the formulation below will include the relocation of the workstation. During the comparison, we will set the relocation time to zero for the free-ranging MHS. Therefore, in this formulation, before launching a new order, it is necessary to clear the production line and relocate the workstations. It is interesting to note, for the purpose of improvement of productivity, that the relocation for launching a new product can be started while some of the work for the existing product is being finished. In our case, we let l be the number of workstations finishing the work for the existing product. Therefore, the average time of each order spent in production is $T_C(Q+[NP_L]-l)+T_R+T_S$. However, the effective time is only QT_C. Therefore, the effective workstation utilization can be formulated as follows:

$$U = \frac{QT_C}{T_C(Q+[NP_L]-l)+T_R+T_S} \tag{11.6}$$

Where P_L denotes the percentage of workstations loaded in an order. Then $[NP_L]$ denotes the total number of workstations required for the new order. Where Q denotes the order size, T_C denotes the cycle time, T_S denotes the setup time, and T_R denotes the total machine relocation time.

Total Transportation Distance (TTD)

TTD, one of the most frequently used criteria for evaluating material handling systems (Sedehi and Farahani 2009), is defined as the weighted sum of material flow distances between different workstations or departments. Suppose the transportation speed is the same and the requirements for the workstation are also the same in different systems. In this case, the minimum material flow distance is valuable for enhancing the utilization of the entire system, reducing the throughput time and the WIP. As a result, this improves the capability of responding to customers' requirements quickly. A detailed analytical formulation of the TTD of the free-ranging MHS and fixed-track systems is given in Dai *et al.* (2008).

11.2.2.3 Structure of the Free-ranging Material Handling System

The main concept of the free-ranging MHS is that it can support free-ranging material handling rather than fixed path material handling. In order to achieve the free-ranging property, the following structure and subsystems are required:

Local Positioning System (LPS)

To support the function of the free-ranging AGV, an indoor local positioning system is required to estimate the absolute position information for the free-ranging AGV. A potentially cost-effective and accurate ultrasonic positioning system was been proposed for navigating AGV by Lee, Chan and Dai in 2008 in an unpublished article. In the ultrasonic positioning system, emitters of ultrasound and radio frequency are placed on the ceiling of the plant, while receivers are placed on the free-ranging AGV. Since the radio frequency propagates much faster than the ultrasound, the synchronously transmitted signals from the same emitter will arrive at the receiver at different times. Based on the time difference of propagation for the radio frequency and the ultrasound, one can determine the distance between the emitter and the receiver. A multilateration method can be used to figure out the position of the free-ranging AGV with multiple transmitters placed at different locations. Many algorithms such as the Karman filter and the particle filter may also be applied to improve the tracking and navigation performance.

Central Controller

A central controller is widely used in the manufacturing industry. In the free-ranging MHS, the central controller is designed for several purposes. Firstly, it can monitor and control the movement of the free-ranging AGV and the entire manufacturing system. Secondly, it may be used to identify failures or problems as well as to optimize the production system. Thirdly, it gives orders to the loading module in workstations by radio frequency to load the materials and at the same time dispatch jobs to workstations. Fourthly, it stores the information of the product or the material which is collected by the RFID.

Free-ranging AGV (FRAGV)

Basically, the function of the AGV is similar to that of a truck. However due to the limited space of paths in the MHS, it is vital for the FRAGV to have the capability of turning 90° to change the orientation in the path without changing its position. Therefore a special design should be adopted. One of the easy ways to provide this tight quarter turning is to use two independent motors for the left and right wheels of the FRAGV. Furthermore, this vehicle is controlled by the central controller discussed above. This can be accomplished by first determining the location of the FRAGV by the LPS. Second, the FRAGV transmitters send this position information to the central controller. Finally, the central controller controls the speed and direction of the FRAGV. The power supply of the motors is provided by a rechargeable battery.

Workstation

In this system, the workstation should be equipped with a loading and unloading system for the FRAGV to bring the material in and out of it. The tray should be used to contain the parts. To track the material flow, RFID or a barcode may be used. To enhance the throughput, a buffer that can hold several trays is used.

Battery Charging/Changing Station

A supportive station should be provided for the FRAGV to charge batteries and exchange charged batteries with the empty ones. To facilitate the automated charging or exchanging of batteries, the FRAGV is required to stop near the battery charging/changing station quickly and accurately. Therefore, a specially designed mechanical track is placed near the station.

11.2.2.4 Methodology of the Free-ranging Material Handling System

The previous section describes the main structure of the free-ranging MHS. In this section, we will discuss the operating methodology of the free-ranging MHS.

1. *Order loading:* when an order has been placed in the production line, the central controller would generate a production plan based on the production process, the bill of materials, the size of the order, and the status of the production line. From this production plan, the material flow requirements will be generated.
2. *FRAGV:* a dispatching central controller will select the FRAGV based on the material flow requirements and the status of the FRAGV such as availability and location.
3. *Routing:* a central controller determines the optimal routing for the FRAGV based on the location and the destination as well as the traffic condition.
4. *FRAGV movement control:* aided by the LPS, the central controller would be able to track the movement of the FRAGV. Then, the central controller chooses the optimal speed and direction for the FRAGV. To reach the planned speed and direction, the central controller controls the input currents to the motors in the left and right wheels.
5. *Traffic control:* to avoid congestions and collisions, the central controller has to coordinate the movement of the FRAGV. LPS and scheduling algorithms play a vital role in this step. Control is realized through the wireless communication with radio frequency.
6. *Part loading and unloading:* once the FRAGV reaches the designated workstation, the operation of loading and unloading takes place. This operation is controlled and monitored by the central controller, aided by the LPS and the RFID technology.
7. *Material tracking:* RFID can be used to track the material flow.
8. *Rerouting operation:* this is a potential advantage of the free-ranging MHS. Sometimes the production line experiences unexpected change of the status in

workstations or FRAGVs, for example, the breakdown of a workstation or FRAGV. In such an instance, the central controller can modify the dispatching and routing order for the FRAGV. The failed FRAGV will be pulled back to the AGV charging and storage station to avoid traffic congestion.

11.3 Industrial Application for the Apparel Industry

The apparel industry generated a total revenue of 1.5 trillion US dollars in 2006 (Datamonitor 2007). It has the properties of small order size and rapidly changing customer demands. Therefore it is extremely demanding for mass customization (Lee and Chen 1999, Le *et al.* 2002). However, due to the intensified challenge of mass customization and increasing labor cost, the apparel industry in the advanced countries or areas has been facing a steady decline recently (Chin *et al.* 2004). In order to streamline their production cycle to better respond to consumers' demand and at the same time to save cost with improving quality, apparel manufacturers are starting to seek new business and manufacturing practice and strategies, among which the improvement of the designing and planning of material handling systems ranks first (Witt 1995).

11.3.1 Existing Material Handling Systems for the Apparel Industry

There is extensive research on automatic handling and manipulation of textile products in the apparel industry. A robotic system is developed for textile-like materials handling in (Paraschidis *et al.* 1994) from the perspectives of handling operations based on version and force/torque sensing. A flexible material handling system with wired AGV, which transports garments from the silkscreen process to the fold-and-pack area, and the conveyor belt, which delivers the boxed goods from fold-and-pack area to the shipping area, have been designed to increase throughput and product quality (Aldrich 1995). The "walking floor", which is a sequentially operated reciprocating floor slat conveyor with typical actuation through three hydraulic cylinders, provides an opportunity to improve the material handling throughput, as reported by Beason (1999). The unit production system (UPS) that transports the material by a hanger-like carrier, increases the efficiency and reduces the WIP level of apparel manufacturing traditional bundling systems (Hill 1994). There are two classical UPS in the market: one is the TUKAtrack Information Tracking System from the United States and the other is the Eton system from Eton Systems in Sweden. Other material handling solutions in the apparel industry include Toyota System-Style (TSS) quick response methods with garments passed by hand, the manual overhead sewing production line in UK-based Peter Ward, and Magic Tube for garment production, handling, warehousing, and transportation systems in Salpomec Ltd. However, Eton Systems from Sweden remains the market leader in the modern apparel industry (Tait 1996).

The Eton system, designed by Inge Davidson, the founder of Eton Systems Inc., is a UPS with computerized overhead conveyer and individually addressable workstations which transports the materials by a hanger-like carrier to increase the efficiency and reduce WIP level of apparel manufacturing. Figure 11.4 shows the appearance of the Eton system. The newest generation of Eton systems is the Eton 5000 Syncro. The main idea of the Eton system is to use a hanger-like carrier to transport the material through the production line. It replaces manual material transportation, which occupies valuable skillful operators' time, by an automated hanger system so that operators can concentrate on their jobs. Figure 11.5 presents the schematic layout of Eton systems. Figure 11.6 presents the layout of two commonly used Eton systems: the simply joined Eton (SJ-Eton) and the joined Eton (J-Eton). If the workstation is assigned a task, the carrier will hand the material to the branch of the workstation, otherwise, the material will be handed to the next workstation directly by the headline. A detailed illustration of Eton systems can be found on the company's homepage (www.eton.se). To identify the proper MHS for mass customization in the apparel industry, the performance of these MHSs is qualitatively compared in Table 11.2. We can observe that the UPS and the MHS using fixed-track AGV outperform other MHSs, which is why these two systems are fairly popular in practice.

Figure 11.4 The Eton system from Sweden

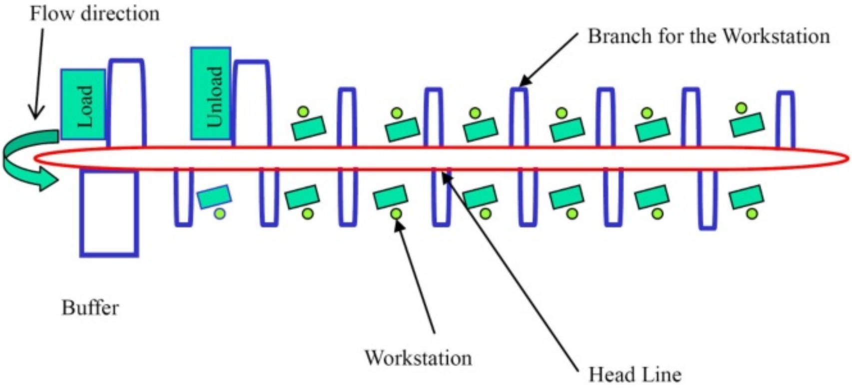

Figure 11.5 Schematic layout of a basic Eton line

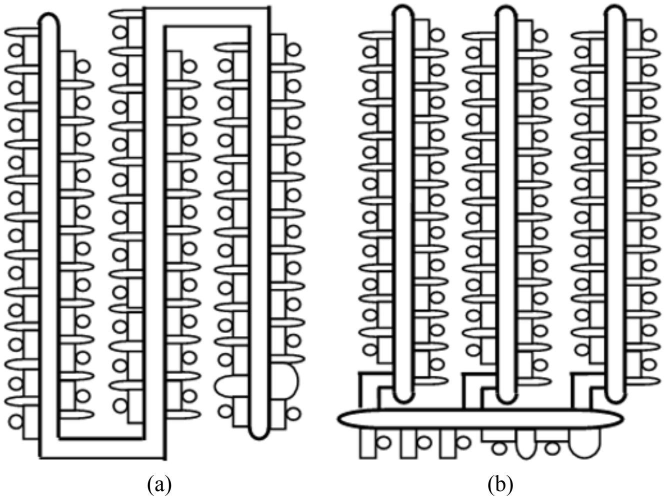
(a)
(b)

Figure 11.6 Configuration of the simply joined Eton system (a) and the joined Eton system (b)

Table 11.2 Summary of material handling systems

System	Flexibility	Speed	Setup cost	Operating cost	Product quality and process reliability
Manual overhead sewing line	High	Low	Low	High	Low
Conveyor belt	Low	High	High	Low	High
Toyota system-style	Low	High	Medium	Medium	High
Progressive bundle	Low	Low	Low	Medium	Low
Unit production system	Medium	High	High	Low	Medium
Fixed track AGV	Medium	Medium	High	Low	High

11.3.2 System Layout Design

Facility layout design has been a very active research area in the past four decades; many optimization models are reviewed in Beamon and Chen (1998), Chittratanawat and Noble (1999). However, most of the models assume that information regarding production quantity and routing path of different products is known in advance. In the apparel industry, the demand is changing quickly and is very difficult to forecast; so in this paper we only focus on constructing the conceptual layout of the free-ranging MHS mainly from the perspectives of approximated system performance and safety. Considering the space dominated by the fixed-track system, we design the layout for the free-ranging MHS, as presented in Figure 11.8. In order for the proposed system to operate properly using a central controller, local positioning system and the FRAGV, we need a special consideration on the system layout, such as safety issues. To avoid the interference of human traffic in our free-ranging MHS, the moving paths for AGVs and humans are separated in our design. As shown in Figure 11.7, the loading and unloading workstations are positioned at the top. The AGV charging station is located at the bottom and the workstations are placed in the center. Each workstation comprises a loading area, which is denoted by a small rectangle, and an operating area, which is denoted by a large rectangle. The workstations are then grouped into subgroups, and a path for the FRAGV in the center connects all subgroups together. The FRAGV can only access the path in the subgroups and the path con-

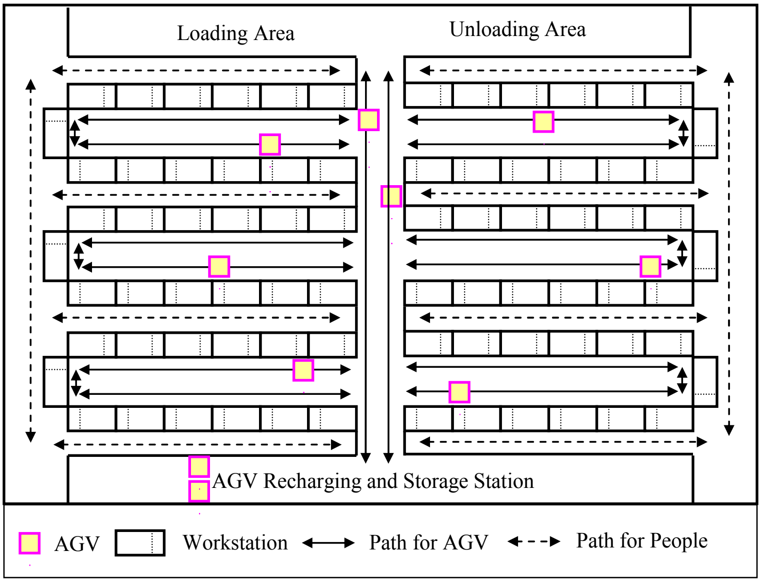

Figure 11.7 Schematic layout of the free-ranging MHS

necting subgroups to transport the material among workstations. The path for the FRAGV can hold two bi-directional paralleling FRAGVs. As a result, once one FRAGV is broken, the other can cross the path to ensure the continuous material handling and avoid congestion due to the specially designed FRAGV, which can flexibly turn 90°. The corridors between the subgroups can only be accessed by the workers. In this case, this design separates people and FRAGVs for safety reasons. Due to the free path property, machines with similar functions can be arranged by function, product, or hybrid layout for easy maintenance and better resources sharing.

11.3.3 Potential Advantages of the Free-ranging Material Handling System

The Monte Carlo simulation approach is adopted for the following reasons. Maione *et al.* (1986) assume that the material handling time, including the traveling and loading/unloading time, is negligible compared to the processing time. However, in apparel manufacturing, the processing time is relatively short, which makes the proportion of material handling time higher. For example, in many sewing factories, 80% of the production time is spent on material handling and only 20% is spent on sewing; thus, it is necessary to take the material handling time into the performance analysis (Wong *et al.* 2005). Therefore, analytical models become invalid and simulation is used to assess the performance of manufacturing systems and material handling systems (Lu and Gross 2001, Qiao *et al.* 2002, Savory *et al.* 1991, Smith 2003). Furthermore, in the apparel industry, since the number of workstations required is usually large, it is unpractical to formulate the simulation using traditional software such as SIMAN and ARENA; thus, discrete time Monte Carlo simulations using MATLAB are formulated to do the comparative study.

To construct the simulation models for the free-ranging MHS and fixed-track systems, several assumptions are required to facilitate the comparative analysis:

1. The processing times follow identical independent normal distributions, and the production line is well balanced.
2. The first workstation is also busy and no preemptive failures occur in the entire system.
3. The speed of handling is fixed no matter whether the FRAGV or carrier is loaded or not.
4. The number of FRAGV and carriers is enough for each order.
5. First in, first out (FIFO) rule is used for all workstations.
6. Workstations with short transportation distance have high priority to be loaded.

Discrete time Monte Carlo simulations using MATLAB are formulated to do the comparative study. This entails the following steps:

1. Given the number of workstations n and the loading percentage P_L, find the minimal number of subgroups. Assign the tasks to the workstations and then figure out the transportation distance d_j from workstation $j-1$ to workstation j.
2. Generate the order size with random variables Q and the service time at workstation j with random variables S_j. Both variables follow normal distribution. When launching a new order, set the starting service time of the first entity $SS_{1,j}$ as the finishing service time of the last order FS_{Q,nP_L} plus the setup time and the relocation time.
3. If the queue length of the workstation j is larger than the designed buffer size C, denoted by $FS_{i,j-1} + d_j / v < FS_{i-C,j}$,
   and then $FS_{i,j-1} = FS_{i-C,j} - d_j / v$, $SS_{i,j-1} = FS_{i,j-1} - s_{j-1}$,
   and otherwise, $SS_{i,j} = \max(FS_{i-1,j}, FS_{i,j-1} + d_j / v)$, $FS_{i,j} = SS_{i,j} + s_j$.

Collect the waiting time W and the total material handling time M, average time in the production line AVT, and the throughput $TH = Q/(FS_{Q.nP_L} - SS_{1,1})$ as follows:

$$W = \frac{1}{Q}\sum_{i=1}^{Q}\sum_{j=1}^{nP_L}(SS_{i,j} - FS_{i,j-1} - d_j / v) \tag{11.7}$$

$$M = \sum_{j=1}^{nP_L} d_j / v \tag{11.8}$$

$$AVT = \frac{1}{Q}\sum_{i=1}^{Q}(FS_{i,nP_L} - SS_{i,1}) \tag{11.9}$$

The other measures can be calculated by these parameters using the model that we defined in the previous section. Repeat from step 2 to ensure that all the measures are converged. Practical inputs of the simulation are shown in Table 11.3. The number of workstations indicates the scale of the production system. The loading percentage measures how many workstations needed for a product. These dimension parameters and speed are used to calculate the material handling time. The buffer size means how many pieces of material may be buffered in each workstation before the processing operation. Each simulation was replicated 200 times with a study period of 24 running hours *per* day to ensure convergence. As a result, in all the performance measurements, the coefficient of variation (CV) is less than 5%.

Figure 11.8 compares the manufacturing system effectiveness of the free-ranging MHS and fixed-track MHSs in flexible manufacturing of small order sizes. The improvement is computed comparing the measures obtained in the free-ranging MHS and the better measures in both the SJ-Eton system and the J-Eton system. We can see that the free-ranging MHS improves the VAE by over 50%, the WIP and the AVT by over 20%, the MCE by over 10%, and the TH by over 3% in producing small orders. The underlying reason is that the free-ranging MHS shortens the setup time and material handling time and therefore the waiting time.

Table 11.3 Input parameters for the simulation example

Input parameters	Value
Number of workstations	60
Processing time (s)	$5 + N(20, 5)$[3]
Order size	$N(200, 20)$
Conveyor speed (m/s)	1.2
Free-ranging AGV speed (m/s)	1.2
Loading percentage	80%
Length of the workstation: LWS (m)	2.2
Width of the workstation (m)	1
Width of the corridor (m)	1
With of the headline (m)	0.8
Length of the workstation branch (m)	1.5
Height of the workstation branch (m)	0.8
Length of the loading and unloading station (λL_{WS})	$3 L_{WS}$
Subgroup size in Eton systems	21
Subgroup size in the free-ranging MHS	13
Buffer size in Eton systems	8
Buffer size in the free-ranging MHS	2
Total setup time (s)	900
Total relocation time (s)	900

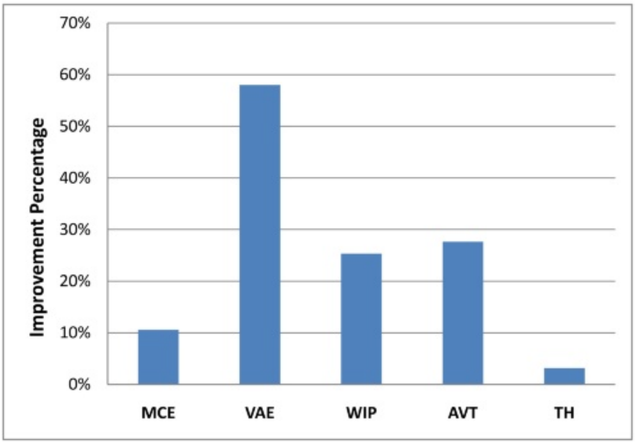

Figure 11.8 Monte Carlo simulation results of comparing manufacturing system effectiveness

Although the free-ranging MHS only improves the TH slightly, it improves the TH in the practical worst case significantly. Based on the simulation results, using (11.4) and (11.5), we can find that the TH in the practical worst case for the SJ-Eton system, the J-Eton system, and the free-ranging MHS are 0:0192 unit/s,

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[3] N(20, 5) indicates a normal distribution with a mean of 20 and a standard variance of 5

$0{:}0195$ unit/s, and $0{:}0227$ unit/s, respectively; therefore the improvement of THC_{PWC} is 16.6%. Moreover, the setup time of the free-ranging MHS is much shorter than that of the Eton systems, so the free-ranging MHS can produce much faster than Eton systems at significantly lower inventory level.

Based on the industry example presented in Table 11.3, the performances of the workstation utilization and the total transportation distance are compared to evaluate the effectiveness of the free-ranging MHS in addressing product proliferation or customization. Results for the workstation utilization comparison are shown in Figure 11.9. For small order sizes, the free-ranging MHS improves the work station utilization by over 10%. The improvement percentage increases as the loading percentage or the order size decreases. This indicates that the free-ranging MHS can produce more at the steady state than Eton systems, and it is extremely effective for addressing product proliferation in the apparel industry, especially when there are multiple orders loaded in the same production system.

Figure 11.10 compares the total transportation distance of the free-ranging MHS and Eton systems under different numbers of workstations and loading percentages. The number of workstations denotes the scale of the manufacturing plant, and the loading percentage denotes different products. We may conclude that the free-ranging MHS shortens the total transportation distance in about 68% under high product proliferation in different manufacturing plants. Therefore it could shorten the material transportation time and then the waiting time. There are two underlying reasons for these results. First, in Eton systems these parts need to pass through the headline in the central loading section, which induces extra traveling distance into the system. However, in the free-ranging MHS, the FRAGV can turn in both directions on the main path. As a result, these parts do not need to travel the full main path to return to the loading station. Second, there is no vertical material flow distance in the free-ranging MHS. The variation in the improvement is due to the fixed-track in Eton systems. In Eton systems, parts are required to go through the entire headline no matter how many workstations are loaded. The handling distance in the headline depends on the number of workstations in the manufacturing plant.

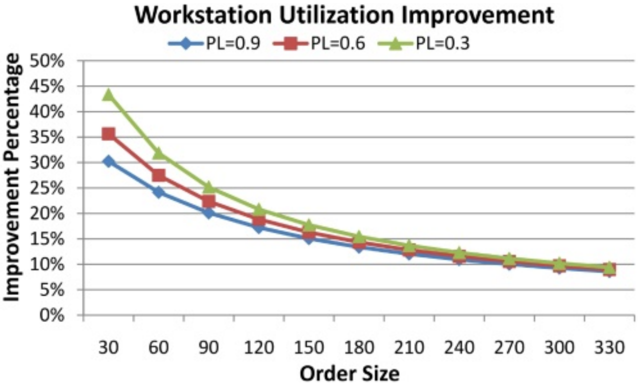

Figure 11.9 Workstation utilization improvement under different loading percentages

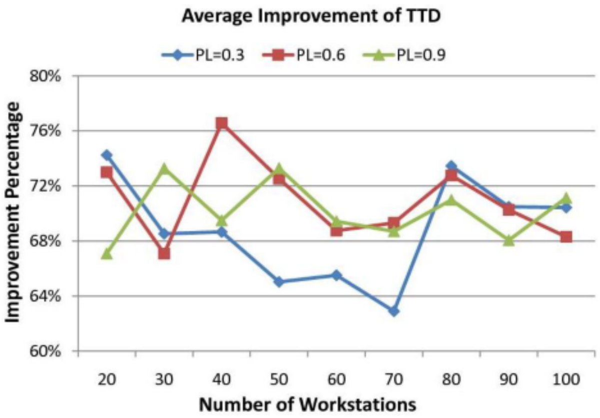

Figure 11.10 Total transportation distance improvement under different loading percentages

11.3.4 Economical Feasibility Analysis on Free-ranging MHS

From the study above, we observe that the flexible free-ranging MHS has potential advantages in the performance measures over the fixed-track MHS. However automatic MHSs are difficult to implement and operate. Therefore the cost–benefit analysis of these automatic MHSs is necessary. Moreover, it might be better to have a manual system that is very flexible with some extra personnel to match the throughput advantages of the free-ranging MHS without the associated machine setup and operating costs. Therefore, the economic feasibility analysis should be conducted by benchmarking performance on the manual MHS.

11.3.4.1 Cost Estimation of Adopting Automatic MHSs

Suppose that currently the manual system is used, and then the objective of the economic justification is to study the project performance of introducing automatic MHSs. To conduct the justification, it is necessary that several costs and benefits be estimated in advance.

Investment

The free-ranging MHS comprises FRAGVs, sensor station, workstation, battery changing/charging station, tracking system, software, and computer system. To estimate the investment of introducing the free-ranging MHS, costing of those components is necessary. A sample FRAGV has been developed in our study. Its cost breakdown is presented in Table 11.4. The total cost of the FRAGV is US $860. This estimation is conservative because actually the cost of the material may be discounted somewhat in mass production. The car manufacturing industry gross profit margin is about 20% in China. It is reasonable to set the gross profit margin of the FRAGV as 40%, and then the selling price of the FRAGV is US $1,204. Since each FRAGV may serve 2–3 workstations, the total number of FRAGVs in the numerical example with 60 workstations is about 25. Supposing there are 20% extra FRAGVs for replacement, the total number of FRAGVs is 30. Then, the total investment of the FRAGV is US $36,120. The sample software has not been developed yet and it may cost 20 Chinese software engineers 2 years to develop. The labor cost of each engineer is about US $15,000 *per* year. Therefore the total cost of the sample software is US $600,000. Suppose the market size is about 50, and then the cost of software is about US $12,000. The gross profit margin of the software industry in China is about 100%. Therefore it is reasonable to set the software gross profit margin as 300% here, and then the investment of the software is US $48,000. Table 11.5 presents the breakdown of the free-ranging MHS investment. The equipment value of the free-ranging MHS is US $158,674. Suppose the installation cost is 10% of the equipment value, and then the total investment of the free-ranging MHS is US $174,541. From the quote of the fixed-track system supplier, the investment including installation cost and training cost is about US $3,000 *per* workstation. Supposing there is a safety factor of 1.3, then the total investment of the fixed-track system is about US $234,000.

Table 11.4 FRAGV cost breakdown

Part	Items	Quantity	Total cost (US $)
Mechanical part	Geared motor and gearbox	2	462
	Battery	2	51
	Wheel and motor adapter	2	26
	Shelf and plastic panel	1	100
	Wheel		41
Wireless electronic part	Ardmino-min	3	13
	Ultrasonic sensor module	1	25
	Magnetic compass	1	49
	Radio frequency module	1	18
	USB transaction	1	6
	Motor control panel	1	19

Table 11.5 Free-ranging MHS investment breakdown

Part	Quantity	Total cost (US $)
FRAGV	30	36,120
Sensor station	60	3,354
Workstation modification	60	30,000
Battery changing/charging station	1	20,000
Tracking system	1	20,000
Software	1	48,000
Computer	2	1,200
Total		158,674

Labor Cost

According to a survey by Hill (1994), the fixed-track MHS such as the Eton system may reduce direct labor by about 9.7% compared with manual MHS; moreover, the ratio of the number of direct labor cost to the number of workstations is 82%. Therefore, the total number of direct labor in the fixed-track MHS is $600 \times 0.82 \approx 49$, while the direct labor cost in the manual system is $49 \div (1\text{–}9:7\%) \approx 55$. The number of direct labor cost in the free-ranging MHS is 49 too because the automatic principle in the free-ranging MHS and fixed-track MHS is similar. Suppose currently the labor rate is US \$2.5 per hour and the fringe benefit as a percentage of payroll is 25%. Then the labor cost of each worker is US \$6,500 *per* year. Therefore, the total annual direct labor cost of the manual system, fixed-track system, and the free-ranging system is US \$357,500, US \$318,500, and US \$318, 500, respectively.

Maintenance Cost

In the manual MHS we assume that there is only one worker in charge of maintenance; according to the labor rate assumed above, the estimated annual maintenance cost is US \$6,500. In fixed-track MHS, more work is necessary for the hanger-like carrier, the track, the tracking system, the software, *etc.* According to the data provided by the fixed-track MHS supplier, the annual maintenance cost is generally less than 1% of the total investment. Therefore it is reasonable to set the annual maintenance cost as $6500 + 23400/100 =$ US \$8,840. Table 11.6 compares the maintenance activities in both fixed-track MHS and free-ranging MHS. Since the maintenance of the FRAGV and the routing system is much more complicated, we assume that the maintenance cost of free-ranging MHS is a factor of 4 comparing with that of fixed-track MHS. In this case, the maintenance cost in the free-ranging MHS is US \$35,360 *per* year.

Table 11.6 Maintenance activities comparison in both fixed-track MHS and free-ranging MHS

Fixed-track MHS	Free-ranging MHS
Hanger-like carrier	Sensor station
Track	FRAGV
Tracking system	Battery
Software	Software
	Battery changing and charging station
	Tracking system
	Routing system

System Change Cost

When the product or the system layout changes, the manual MHS and the free-ranging MHS is flexible enough to address these challenges. However, the fixed-track MHS is not flexible enough, and therefore system change is necessary. In the system change process, parts are removed and then installed in another location;

moreover, the production is delayed. Therefore, we assume that the system change cost is twice the installation cost. According to Hill (1994), the installation cost accounts for 16.6% of the original value of the equipment, and then the system change cost is $2 \times 234000 \div (1 + 16{:}6\%) \times 16{:}6\% \approx \text{US } \$66{,}628$.

Salvage Value

According to Hill (1994), the salvage value of the fixed-track system is 25% of the original value of the new equipment; moreover, as reported by the fixed-track MHS supplier, the useful life is at least 10 years. In the free-ranging MHS, the major parts are the FRAGV and the software. The FRAGV has a useful life of about 5 years because the motor and gearbox can usually work about 5 years. Since the electronic components usually do not fail in 5 years, we assume that the salvage value of the free-ranging system is about 20% of the original value of the new equipment.

Productivity Improvement

Productivity improvement may bring the benefit of a corresponding ratio of labor cost savings to match the throughput of the manual MHS. However, productivity improvement has no effect on the maintenance cost. According to users' feedback, fixed-track MHS generally can enhance the productivity by 30–40% and sometimes even 100%. Here we assume that the productivity improvement is 30%. From the potential advantages analysis in Section 11.3.3, the free-ranging MHS may enhance the productivity over the fixed-track MHS by about 3% under different order sizes. Therefore, free-ranging MHS may improve the productivity by about 33.9% over manual MHS.

All the material handling resources in these three systems are summarized in Table 11.7.

Table 11.7 Material handling resources

Items	Manual MHS	Fixed-track MHS	Free-ranging MHS
Total investment	0	US $240,000	US $174,541
Direct labor cost	US $357,500	US $318,500	US $318,500
Maintenance cost	US $6,500	US $8,840	US $35,360
Cost saving (productivity improvement)	0	US $73,7500	US $80,635
System change cost	0	US $66,628	0
Salvage value	0	US $58,500	US $43,635

11.3.4.2 Capital Investment in Automatic Material Handling Systems

From the cost estimation above, if there is no system change, in fixed-track MHS, he annual cost saving is $375500 + 6500 - (318500 \div (1 + 30\%) + 8840) =$ US

$110,160. Similarly, in free-ranging MHS, the annual cost saving is US $90,776. Table 11.8 presents the incremental cash flow in automatic MHSs compared with manual MHS. A modified accelerated cost recovery system (MACRS) as a common method of accelerated asset depreciation is used. Based on the incremental cash flow, Tables 11.9 and 11.10 show the after-tax present worth analysis of fixed-track MHS and free-ranging MHS, respectively. The incremental cash flow is the before-tax cash flow (BTCF); after tax deduction, the after-tax cash flow (ATCF), which is used to evaluate the economic performance, is generated. Since these two systems have different useful life, the automatic MHS adoption project may compared by the internal rate of return (IRR) and payback years. Table 11.11 shows the justification results. Both fixed-track MHS and free-ranging MHS have an IRR larger than 15%; moreover, the reasonable payback years indicate a reasonable risk of the investment. This means that it is profitable and safe to adopt automatic MHSs. Currently the IRR of fixed-track MHS is larger than that of free-ranging MHS, which indicates that when there is no system change and the labor rate is US $2.5 *per* hour, the fixed-track MHS may have better economic performance.

Table 11.8 Incremental cash flow

Items	Fixed-track MHS	Free-ranging MHS
Capital investment	US $240,000	US $174,541
Annual cost savings (before taxes)	US $110,160	US $90,776
Salvage value	US $58,500	US $43,635
Useful life	10	5
MACRS property class	7	3
Corporate income tax rate	25%	25%
After-tax minimum attractive rate of return (MARR)	15%	15%

Table 11.9 After-tax present worth analysis of the fixed-track MHS

Year	BTCF (US $)	MACRS depreciation (US $)	Taxable income (US $)	Income taxes (US $)	ATCF (US $)
0	−234,000				−234,000
1	110,160	−25,079	85,081	21,270	88,890
2	110,160	−42,980	67,180	16,795	93,365
3	110,160	−30,695	79,465	19,866	90,294
4	110,160	−21,920	88,240	22,060	88,100
5	110,160	−15,672	94,488	23,622	86,538
6	110,160	−15,655	94,505	23,626	86,534
7	110,160	−15,672	94,488	23,622	86,538
8	110,160	−7,827	102,333	25,583	84,577
9	110,160		110,160	27,540	82,620
10	110,160		110,160	27,540	82,620

Table 11.10 After-tax present worth analysis of the free-ranging MHS

Year	BTCF (US $)	MACRS depreciation (US $)	Taxable income (US $)	Income taxes (US $)	ATCF (US $)
0	−174,541				
1	90,776	−43,631	47,145	11,786	78,990
2	90,776	−43,631	32,588	8,147	82,629
3	90,776	−43,631	71,389	17,847	72,929
4	90,776	−43,631	81,076	20,269	70,507
5	90,776	−43,631	90,776	22,694	68,082

Table 11.11 Economic justification results

Items	Fixed-track MHS	Free-ranging MHS
IRR	36.37%	33.47%
Payback years	3.5	2.9

11.3.5 Sensitivity Analysis on Adopting Automatic MHSs

Due to high product proliferation and MC, it is necessary for the production system to suit different products. Since fixed-track MHS is not flexible enough, system change cost will occur when the system layout or product changes. In this case, the economic performance of fixed-track MHS will be worse. Therefore, it is necessary to study this risk on different system change cycle times. Table 11.12 shows the sensitivity analysis results on different system change cycle times. From the table, we may observe that when the system change cycle time is no less than 4 years, fixed-track MHS may have better economic performance. However, when the system change cycle time is less than 4 years, free-ranging MHS may be more promising. Currently, the labor rate used is US $2.5 *per* hour. However, for a ong-term project, the labor rate often changes. Increasing the labor rate may affect the annual cost savings in adopting automatic MHSs and then affect the economic performance of adopting automatic MHSs. Therefore, it is necessary to study the project performance with different labor rates. Here, we assume that the system

Table 11.12 Sensitivity analysis on system change cycle times for adopting the fixed-track MHS

System change cycle time (years)	IRR	Payback years
1	17.61%	8.1
2	28.53%	4.6
3	32.10%	4
4	33.79%	3.9
5	34.59%	3.5
6	35.31%	3.5
7	35.59%	3.5

change cycle is 3 years. Table 11.13 presents the sensitivity analysis results on different labor rates. In the case where the system change cycle time is 3 years, when the labor rate *per* hour is no larger than US $1.5, automatic MHSs are not recommended to adopt based on the after-tax MARR of 15%. When the labor rate *per* hour is larger than US $1.5, both automatic MHSs are promising. However, when the labor rate *per* hour is less than US $2.5, fixed-track MHS may have slight potential economic advantages, and when the labor rate *per* hour is no less than US $2.5, free-ranging MHS may be more promising.

Table 11.13 Sensitivity analysis on labor rate when adopting automatic MHSs

Labor rate per hour (US $)	Fixed-track MHS		Free-ranging MHS	
	IRR	Payback years	IRR	Payback years
1,5	13.13%	> 10	9.26%	> 5
2	23.27%	6	21.97%	3.9
2.5	32.10%	4	33.47%	2.9
3	40.41%	3.2	44.22%	2.3
4	56.19%	2.1	64.38%	1.7
5	71.41%	1.6	83.48%	1.3
6	86.36%	1.3	101.96%	1.1
7	101.15%	1.1	120.06%	0.9
8	115.86%	1	137.91%	0.8

11.4 Conclusion

In the designing and planning of a flexible MHS for MC, there are some factors such as product variety and order size that should be considered. For example, if there is high product proliferation, with the availability of free-ranging MHS, free-ranging MHS would be a good choice for the apparel industry with small order size. In addition to the potential advantages analyzed above, the free-ranging MHS has other benefits:

1. Since there is no physical boundary between production groups, resources such as idle workstations can be shared by different production lines.
2. The efficiency and effectiveness of a production line with parallel workstations can be enhanced. The queue for parallel workstations can be shared, which ensures that parts will follow on a first come first serve basis. This can help the supervisor to quickly identify potential problems. Moreover, it facilitates the flexible real time rescheduling of FRAGV and workstations.
3. Due to the free-path property of FRAGV, similar functions can be grouped together for better resource sharing, which is convenient for expanding production capacity.
4. Like fixed-track MHS, the proposed free-ranging MHS can also improve the utilization of labor resources significantly by replacing manual material handling

by automated material handling through FRAGV. Parts are tracked by the attached RFID tags and therefore they may be taken off the production line anytime without messing up the parts' information in the central controller.

In conclusion, the detailed designing and planning of free-ranging MHS is presented for MC. As an illustration, to evaluate the effectiveness of the free-ranging.

MHS, Monte Carlo simulation and analytical models are developed to compare its performance with that of the fixed-track systems, which are widely used in the apparel industry. Our analysis shows that the free-ranging MHS has substantial potential advantages over the fixed-track systems in terms of manufacturing system effectiveness, workstation utilization, and the total transportation distance. Free-ranging MHS can streamline the manufacturing process, lower the inventory cost, and have the capability of fast responding to customer demands and flexibly suiting various products and volumes of orders. Due to product proliferation, this potential advantage is important in the apparel industry.

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Chapter 12
Design for Changeover (DFC): Enabling Flexible and Highly Responsive Manufacturing

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Abstract A highly flexible manufacturing capability is central to the paradigm of mass customisation. In turn the role of rapid, high quality changeovers is crucial to this capability, whereby production can be switched with minimal penalty across a full (and expanding) range of product offerings. Many companies will seek better changeovers principally by refining the way that personnel complete assigned tasks. Further improvement opportunity can be sought by amending the design of process equipment. By means of focused design improvement an inherently more flexible manufacturing system can become available, on which simpler, more repeatable and faster changeovers can routinely take place.

Abbreviations

CE	Change elements
DFC	Design for changeover
DFMA	Design for manufacture and assembly
DF-X	Design for X
MAS	Manufacturing Advisory Service
MAS-SW	Manufacturing Advisory service South West
OEM	Original equipment manufacturer
SMED	Single minute change of die
UK	United Kingdom

12.1 Introduction

Whether to serve *mass customisation* or the requirements of alternative paradigms of modern manufacturing practice, an enhanced changeover capability has long been acknowledged to have a key enabling role, permitting rapidly achieved production of alternative products from a company's full product range (Sethi and Sethi 1990). This chapter will briefly assess facets of mass customisation alongside those of alternative manufacturing paradigms, emphasising the significant role that a leading changeover capability has. It will then discuss that although various changeover improvement methodologies are in use by industry, these methodologies predominantly concentrate upon organisational refinement, most notably through seeking to externalise as many changeover tasks as possible. The use of design to assist changeover capability is argued to be undervalued. Although some authors have earlier discussed employing design to enable better changeovers

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(Smith 2004, Van Goubergen and Van Landeghem 2002), no comprehensive design for changeover (DFC) methodology is known to have been previously developed, beyond prior work published by University of Bath researchers (Reik *et al.* 2006a–c). The utility of other well known DF-X tools such as DFMA (design for manufacture and assembly) indicates this to be a potentially important omission.

In the years since initial publication (Reik *et al.* 2006a) the University of Bath team has significantly revised the basis of the DFC methodology, seeking to make it more repeatable in use and offering clearer guidance towards the most situation-relevant improvement opportunities. It remains a metric-driven methodology, but is now, as shall be detailed, more coherently structured to assist designers to realise key generic design improvement opportunities. The primary objective of the chapter is to summarise the revised DFC methodology. The chapter will describe the motivation for this work and provide an outline of the theory which underpins it. A summary case study is also presented to illustrate how the methodology has been applied in industry. Space restrictions, however, limit what can be presented and realistically exclude adoption of the methodology based only on what is written in the current chapter. For example, limited space prevents a comprehensive explanation of the mathematical analyses which generate the DFC indices, where the DFC indices in turn guide where iterative design improvement is most advantageously sought. Other important details have similarly had to be omitted but are available upon request to the authors.

12.1.1 Change Drivers: Forces to Change Manufacturing Systems

As well as seeking improvement to the cost, quality and delivery of their products, companies are also increasingly seeking a heightened ability to react to the many uncertainties they will inevitably encounter (Wiendahl and Heger 2003). That companies seek such an enhanced capability is reflected in the literature, with terms such as flexibility, responsiveness, agility, changeability and reconfigurability becoming watchwords of modern manufacturing (Slack 1990, Womack *et al.* 1990, Schuh *et al.* 2004, Kidd 1995). The better that a company (notably including its manufacturing processes) can respond to a changing environment, the greater the long-term commercial success it can expect to enjoy.

12.1.2 The Nature of Uncertainty

Research has been completed to understand the nature of the many uncertainties a business might face. For example, uncertainty has been investigated in mass customisation texts (Pine 1992, Tseng and Jiao 2001, Kaplan and Haenlein 2006), where manufacturing operations are encouraged that enable high levels of responsiveness to changes in customer demands. This in itself though is not sufficient, and the same business must also continue to react to changes arising from environmental, regulatory, economic and other influences (De Toni and Tonchia 1998). These many influences might all dictate necessary changes to a manufacturing system and can together be referred to as change drivers (Neuhausen 2001, Schuh *et al.* 2004).

Wiendahl and Heger (2003) differentiate between direct and indirect change drivers, proposing that many problems manufacturers face are indirectly forced upon them by erratic short cycle changes in one or more of the environment, society, politics and the world economy. They similarly cite that the research and technology resource that is available to the company can also be influential. With parallels to Wiendahl and Heger's work, Neuhausen (2001) distinguishes between external and internal change drivers, each of which have an influence on the design of overall manufacturing systems. Internal change drivers are revisions to company targets, the product programme or the product itself. External change drivers, on which the company has no direct influence, can likewise dictate necessary adaptation of manufacturing processes. Manufacturing systems can range from a single workstation through to global manufacturing networks combining several manufacturing sites, or even several co-ordinated manufacturing companies.

12.1.3 Changeover Assisting Business Response to Uncertainty

A company's overall product manufacturing programme for a forthcoming period defines the necessary capacity requirements for its production system. The design of individual products is similarly fundamental to the design of the production system, where each product must be capable of efficient manufacture. With a wide product offering it is almost inevitable that a company will undertake the manufacture of product families using common manufacturing facilities. These facilities require to be changed over as swiftly as possible and to the highest possible quality (Mileham *et al.* 1999), thereby ensuring minimal disruption as production in ever smaller batch sizes is pursued.

Any specific uncertainty, for example unforeseen patterns of customer preference or changing raw material cost, can impinge upon what product is offered and how that product is delivered, importantly including the manner and speed of its delivery. Whether, for example, a customer-centric manufacturer who is responding to fluctuating high street fashion (Christopher *et al.* 2004) or a manufacturer configuring to supply a major automotive company (Salvador *et al.* 2004), there remains a need (amongst other imperatives) for a company to be able to rapidly adapt its production operations. The importance of responsive small batch flexibility can be underestimated. Studies by University of Bath researchers have shown that a financial benefit to a business exceeding £1m *per annum* can be possible, even when comparatively modest changeover improvement targets are achieved (McIntosh *et al.* 2001).

12.2 Modern Manufacturing Paradigms

Whether to enable viable mass customisation or whether undertaken in pursuit of other goals, an improved changeover capability almost universally remains an attractive outcome to multi-product manufacturing businesses. A brief review of mass customisation and other manufacturing paradigms is presented, where a leading reaction to uncertainty is frequently explicitly described in the literature.

Flexible manufacturing (Slack, 1990, Goldhar and Jelinek 1985) aims for a production system wherein there is a ready ability to change the mix, volume and timing of its output. Within this approach, flexibility has two dimensions, namely range and response. The range flexibility is the range of states a manufacturing system can adopt in terms of the number of different products and their output levels. The response flexibility describes the ease with which a system can be adapted from one state to another. Changeover is of particular significance to response flexibility (Mehrabi *et al.* 2000).

Responsive manufacturing (Matson and McFarlane 1998) describes how a manufacturing system or process reacts to disturbances in its environment. As earlier noted, disturbances can for example be introduced by suppliers, including delivery delays, or by deficiencies in supplied material. Internal disturbances can arise from problems with internal information, control, decision-making, production equipment, labour, and material handling and flow. Further disturbances are possible, from specific customers or the market as a whole. For example, there may be changes to orders, unforeseen variation in demand or forecasting errors.

Lean manufacturing was prominently introduced to the West through the work of Schonberger (1982) and Hall (1983). The term "lean" was coined by Womack *et al.* (1990) to describe the paradigm's main aim, namely the reduction of waste throughout a company's value stream. For some promoters an externalised focus is employed where lean is not just a set of tools for the reduction of waste, but rather represents a set of tools to maximise benefit to the customer (Bicheno 2003). With an internal focus upon factory operations, waste (non-production) associated with changeover activity can readily be identified (Feld 2000).

Reconfigurable manufacturing: shorter product life-cycles and greater product variety place demands upon manufacturers to find new ways to maximise their equipment's cost effectiveness (Urbani *et al.* 2003, Wiendahl and Heger 2003). Modular approaches to system design not only enable flexible processes but also provide manufacturers with the ability to alter processes by rearranging modules of the manufacturing system (Schuh *et al.* 2004). Since reuse of expensive manufacturing equipment is enhanced, the cost effectiveness of manufacturing hardware can be increased substantially. Changeover is fundamentally still taking place to enable new products to be manufactured, but now involves the introduction entirely new pieces of production equipment rather than just adapting parts of existing equipment or an existing process line.

Agile manufacturing: flexibility and responsiveness are important elements of agile manufacturing (Gould 1997). More than just reacting quickly to environmental change, companies instead will seek both to respond to change and exploit change (Booth 1996, Kidd 1995). Enabling tools and methods are identified (Gunasekaran 1998), many of which overlap with those employed under alternative manufacturing paradigms. An objective of reconfigurable manufacturing systems to provide a necessary level of agility has been reported (Gould 1997).

Mass customisation and personalisation: mass customisation seeks to enable businesses to exploit market trends for greater product variety and individualisation (McCarthy 2004). The tools of mass customisation can substantially enable product personalisation (Montreuil and Poulin 2005). Once again, faced with an objective for efficient, flexible, multi-product manufacture, a need for rapid and high quality changeovers becomes paramount (McIntosh *et al.* 2010). Mass customisation and personalisation are a response to the micro-segmentation of markets and require that changed practices for manufacturing and marketing are introduced across the whole of the supply chain (Coronado *et al.* 2004).

Changeability in the Production System

Changeover capability of manufacturing equipment can be positioned as an element within a wider view of production system "changeability". Although the above paradigms address different aspects of manufacturing, they all aim to increase a company's ability to adapt to the influence of change drivers. In other words they aim to increase the changeability of a manufacturing enterprise or parts of that enterprise. This changeability can be seen to affect different levels of a company, from the company as whole (perhaps as a network of manufacturing locations) through to a single processing unit or workstation. Overall five distinct levels of a production system have been identified by different authors (Zhao *et al.* 1999, Neuhausen 2001, Wiendahl and Heger 2003, Nyhuis *et al.* 2006). The current authors' amalgamation and interpretation of these levels is listed below:

1. *production system level 1:* the production network or enterprise level;
2. *production system level 2:* the factory, facility or site level;
3. *production system level 3:* the sub-factory, manufacturing or logistics area level;
4. *production system level 4:* the manufacturing system or group of workstations level; and
5. *production system level 5:* the processing unit or single workstation level.

If a company wants to be able to react to perturbations initiated by the previously described change drivers, then sufficient "changeability" is required across all levels of its operations. For many businesses, a parallel capability will similarly need to be in place in the businesses it engages with, particularly those as part of its supply chain. Wiendahl and Heger (2003) and Nyhuis *et al.* (2006) combine these different levels of a company with a similar classification of different levels of a product:

1. *product level 1:* product portfolio;
2. *product level 2:* individual product;

3. *product level 3:* sub-product;
4. *product level 4:* single component part of a product; and
5. *product level 5:* feature of a part or component.

The combination of these two classifications permits five different types of changeability to be identified, as illustrated in Figure 12.1.

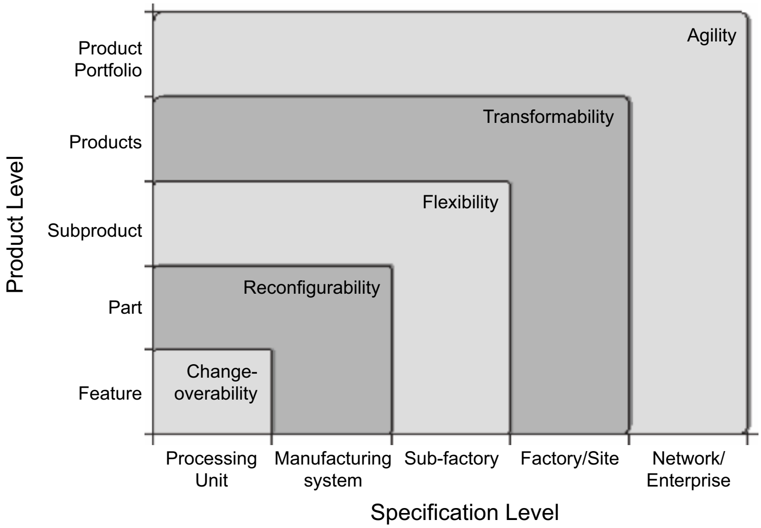


Figure 12.1 Types of changeability (from Nyhuis *et al.* (2006) and Wiendahl and Heger (2003))

Agility stands for the strategic ability of an entire enterprise to open up new markets, to develop the requisite product and service portfolios, and to build up the necessary production capacity. It is desirable that such activity be proactively undertaken.

Transformability describes the tactical ability of an entire factory or site to switch either reactively or proactively to other products.

Flexibility refers to the tactical ability of an entire sub-factory to switch reactively and with reasonably little time and effort to new, but similar, families or sub-products by changing manufacturing processes, material flows and logistics functions.

Reconfigurability describes the practical ability of a manufacturing system to switch reactively and with minimal effort and delay to the manufacture of particular parts through the addition or removal of single functional elements within the system.

Changeoverability describes the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment, again with minimal effort and delay.

The higher levels of changeability build upon the lower levels. In this view agility of an enterprise and its product portfolio is only possible if changeability is sufficient in all the subordinate levels of both the enterprise and the product. The base level changeoverability is the technical capability of manufacturing equipment to flexibly carry out manufacturing processes on features of parts and assemblies. It can be seen as a single core capability which is required for all higher levels or forms of changeability to be successful.

12.3 DFC: Problem Definition and Background

A leading changeover capability is seen to be fundamental to mass customisation, enabling production to switch without undue restriction across all of a company's products, hence assisting highly individualistic satisfaction of customer need. Existing tools to aid achieving a leading changeover capability are known, most particularly Shigeo Shingo's widely adopted SMED (single minute change of die) methodology (Shingo 1985). The authors have previously reported use of the SMED methodology, which in many instances is perceived in industry as inseparable from "changeover improvement" itself, in other words being an applicable tool that addresses all possible improvement opportunities (McIntosh *et al.* 2000). Yet it is a tool that focuses on retrospective improvement and, predominantly, at least in the way that it is typically adopted, is substantially directed towards refining changeover work practice. Most particularly it concentrates upon re-sequencing when individual changeover tasks are conducted, prompting as many as possible to be externalised, hence being completed before production of the current batch ends. Focus is not necessarily on simplifying these tasks, nor reducing the number of tasks which comprise the changeover (McIntosh *et al.* 2000).

Beyond Shingo changeover improvement has been addressed by other authors such as Sekine and Arai (1992), albeit often, in the methodologies they propose, with a significant acknowledgement of Shingo's contribution. Further authors though have presented a stronger design focus on improvement opportunities, for example concerning die changeover in press tools (Smith, 2004). In this case, task simplification and a drive for there to be fewer changeover tasks can become more prevalent. Opportunity is presented for designers to respond at the outset to user needs for responsive, small batch manufacturing by providing changeover-capable machines, rather than necessitating retrospective amendment once machinery has been installed. McIntosh *et al.* (2001) note that such retrospective amendment has often been found to be difficult to financially justify and therefore does not always satisfactorily occur. Other authors still have provided a set of design for changeover rules, presenting these rules as stand-alone guidance without deriving an applicable methodology in which they can be sited (Van Goubergen and Van Landeghem 2002).

As an example of what can be achieved through a design-led approach the authors have researched changeover of large automotive presses. Those being operated by two well known European companies were witnessed enduring changeovers in the range of 10–20 min. Improvement was still being sought, with strictly limited success, by means of in-house SMED teams. By contrast the Japanese press manufacturer Hirotec reports a designed-in changeover capability of 30 s for equipment intended for similar body panel production (Hirotec 2009). The authors have spoken to automotive engineers who have witnessed this claimed capability of Hirotec equipment. A purpose of the DFC methodology is to guide machine designers in all industries towards similar levels of changeover capability.

Motivation: Developing the DFC methodology

Just as certain design for-X tools such as DFMA (design for manufacture and assembly) have proved their value to industry, so too the development of a coherent DFC methodology, outlined in the current paper, is anticipated to be of considerable industrial benefit. No DFC methodology is hitherto known to exist. It is argued elsewhere by the authors (McIntosh *et al.* 2001, 1996) that design-led changeover improvement opportunities are typically undervalued. For original equipment manufacturers (OEMs) the option to supply changeover-proficient equipment new to a user is frequently neglected (McIntosh 1998). The authors note that the work reported in the current chapter is a significant advance on an earlier published version of the University of Bath's DFC methodology (Reik *et al.* 2006b, c).

12.4 An Outline of the University of Bath DFC Methodology

Figure 12.2 presents an outline schematic of the separate steps of the DFC methodology. The methodology is intended to be adopted both by OEMs and practitioners seeking retrospective improvement of existing process hardware. Figure 12.3 provides more detail of the methodology's iterative loops. The methodology is primarily focused on the design of process equipment. Together with a brief ensuing discussion, including later presentation of an overview case study, Figures 12.2 and 12.3 describe the methodology's staged use. The current chapter additionally presents some of the underlying logic of the methodology, which has been successfully trialled in industrial situations where simplicity of use as well as utility is paramount. It extends awareness of changeover improvement opportunities over and above those typically highlighted by traditionally adopted changeover improvement tools, most notably Shingo's SMED methodology. Figures 12.2 and 12.3 show the DFC methodology's use of indices. Summary descriptions of DFC indices ant other major concepts upon which the methodology is founded follow. The figures show the sequential staging of analysis and consequential iterative design refinement to achieve a robust solution to the overall machine design problem.

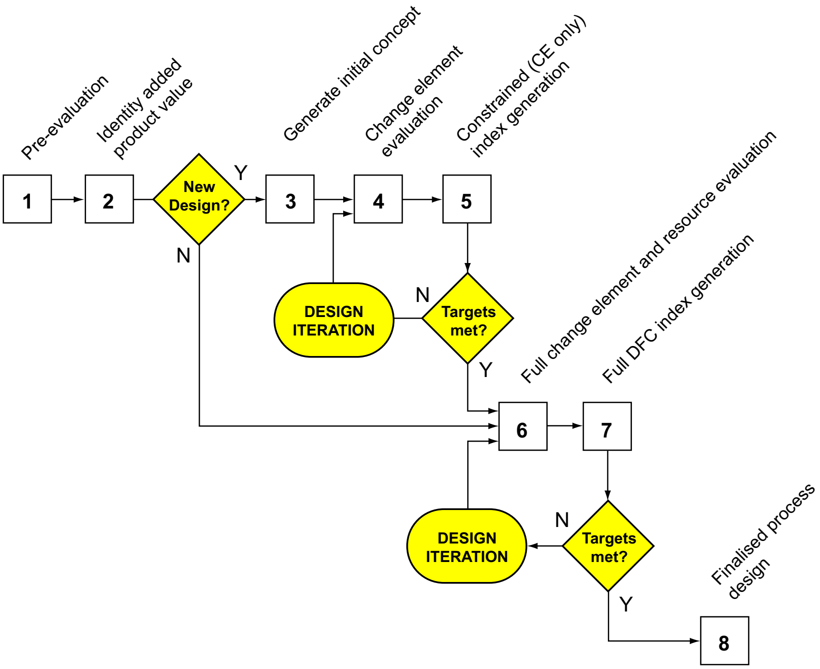


Figure 12.2 A preview of the full DFC methodology (showing two iterative loops)

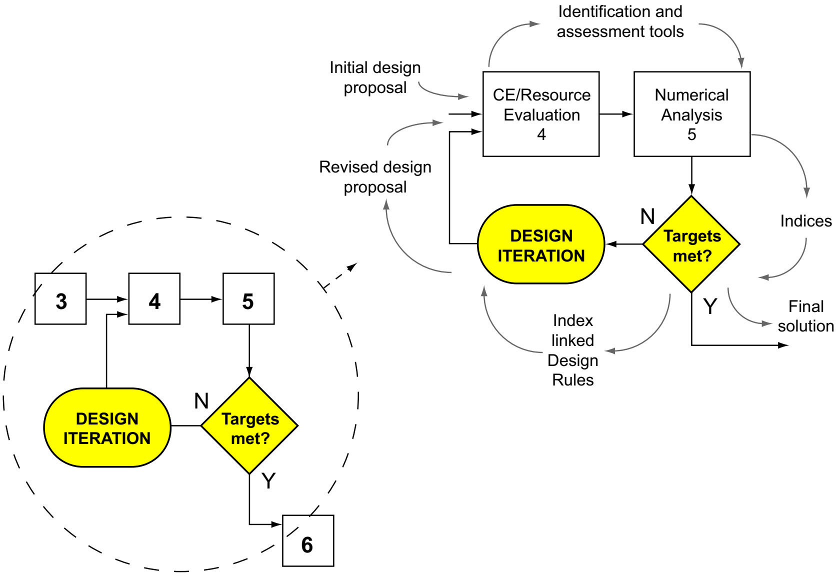


Figure 12.3 Expanded detail of an iterative loop

12.4.1 A Deliberate Avoidance of the Identification of Individual Changeover Tasks

The DFC methodology can be contrasted with many existing DF-X (design for X) methodologies in that it deliberately makes no direct assessment of any individual changeover task which operatives undertake. For example, a task might be to adjust the position of a stop bar, but the DFC methodology will not seek to categorise this or any other task, nor assess its duration. One major problem this approach thereby avoids is defining what constitutes a task. For example, adjusting the stop bar might be a task. Yet at a higher level the full removal of a die set might be conceived as a task. Or, at a much more detailed level, retrieving a hand tool from a tool box might be perceived as a single changeover task, which similarly has to be evaluated and preferably quantified. Ensuing difficulties are also avoided, namely unambiguously assigning a description (moving, placing, aligning, adjusting, lifting, carrying, *etc.*) of the changeover tasks and, further, assigning meaningful and repeatable assessment attributes to those task descriptions.

Instead of a task-led assessment the DFC methodology is based on the simple concept of achieving correct interfaces between all the various machine elements (like the stop bar) that various resources such as personnel or hand tools must act upon. Once all interfaces (typically location) of these machine elements are correctly achieved the machine is ready for production use. By avoiding difficulties inherent in defining what constitute changeover tasks this conceptual approach greatly eases analysis, and in turn eases guiding where design improvement opportunities lie. Elaboration is provided in the following discussion and later *via* the case study.

12.4.2 The Concepts of Resources and Change Elements

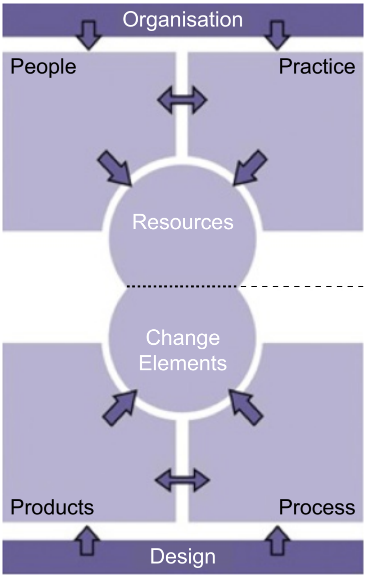
The methodology embodies the concepts of *resources* and *change elements* (sometimes abbreviated as CEs). Resources are needed to undertake the changeover. They can include for example personnel, hand tools, cranes and measurement devices. Change elements are the separate hardware entities which are acted upon by resources when conducting the changeover. Change elements, like the previously mentioned stop bar, whether for example being adjusted or substituted, should normally be identifiable from a machine's parts list. With changeover improvement being influenced by the 4Ps of people, practice, process and product (Riek *et al.* 2005), Figure 12.4 shows that design improvement can be sought to both the process (manufacturing hardware) and to the product to raise changeover capability.

12.4.3 The Concept of Interfaces

The methodology identifies that changeover is complete when all change elements have achieved their necessary new interfaces, both with other change elements and with all further machine entities. These further machine entities are not acted upon during changeover and therefore remain in a fixed relationship to one another and hence in an unaltered state. They are collectively referred to as the equipment platform. In a majority of circumstances achieving necessary new interfaces will simply mean that all change elements are amended into their correct location relative to other change elements and relative to the equipment platform.

12.4.4 Further Description of Change Elements

Figure 12.4 indicates that changeover improvement can be sought by organisational refinement or by redesigning the hardware that is worked upon. Thus attention can be concentrated on what resources are allocated and how and when these resources are employed. Or attention can be concentrated on seeking to redesign the change elements that these resources act upon. Each change element is a clearly identifiable physical entity which is acted upon by resources such as a changeover operative. A change element may be a single component or a collection of components that are always (during changeover) retained together in a fixed relationship as a single entity.



Necessary changeover activities (tasks) are determined by the resources and change elements involved

Figure 12.4 Resources acting upon change elements

For example, a screw might be released and then later reset back as it was before. Or a spacing bar might be entirely removed from the machine, to be substituted by an alternative spacing bar. The interfaces of the screw and of both spacing bars, all of which are change elements, are altered. Change elements are the only entities that need to have their interfaces altered to complete a changeover. Therefore operators will only work on change elements when only completing necessary tasks. Resources in total, including the operator(s), act upon the change elements and enable the completion of new change element interfaces. At completion of the changeover all change elements will become either an integral part of the process or will become (if substituted) fully detached and isolated from it.

12.4.5 DFC Indices and DFC Design Rules

The DFC methodology employs a number of *indices* which all assume a value between 0 and 100. By use of indices the designer is informed as to the likely changeover capability of a proposed machine. The methodology's various indices are aligned (as shown later by Figure 12.7) with individual *DFC design rules*. In the event of a weak changeover capability the designer is directed where best to focus attention by the occurrence of low index scores. The DFC indices and the aligned DFC design rules together thus prompt how design improvement can most advantageously be sought.

Index scores will alter after each iterative design revision, rising as the design improves, and only when all index scores are satisfactory should the designer conclude the design exercise. Indices are derived from substantially unambiguous and simply accumulated information relating to the number of change elements of different types present (description of the different types of change element is beyond this current DFC overview) and whether certain conditions are either present or absent with the change elements and in the use of resources. The primary DFC index is the capability index, which indicates the overall changeover capability of the proposed design. The capability index is derived from an assessment of the total number of change elements present. If a low capability index is generated (if the total change element count is unacceptably high) the designer is prompted to seek to reduce the occurrence of change elements in the design, leading in turn to a likely reduction in the overall level of necessary activity to complete the changeover.

Five merit indices additionally qualify where improvement opportunities predominate for the current design iteration. Their purpose is to draw attention to deficiencies (opportunities) present in the design based on an analysis of change element features and resource use when acting upon those change elements. This activity is assisted by completion of the methodology's design infringement matrix, as detailed below.

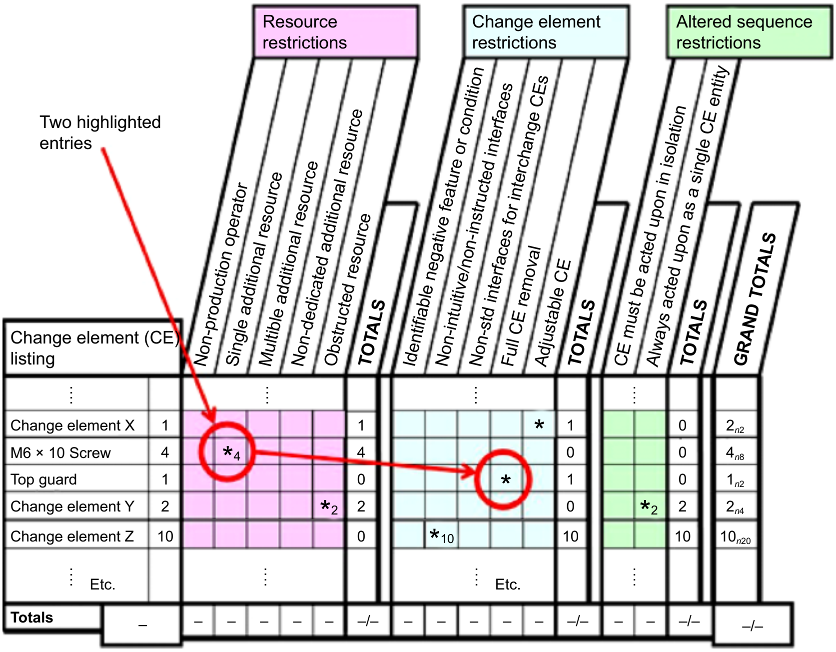
For every index a score of 100 determines that the design is optimal. For all indices the greater the respective opportunity (the greater the determined deficiency relative to prescribed optimum design practice) the lower the index score will be.

All merit indices should attain a score of 100 before the capability index becomes fully representative. The mathematics employed to generate the capability index are relatively complex, but serve the simple purpose of describing a generic curve, an example of which is later presented as Figure 12.6. The capability index curves adopted by the DFC methodology are empirical.

Spreadsheets are available such that index derivations which involve relatively complex mathematical formulae can be invisible the methodology user. In this case, only simply determined criteria of the current design iteration need be entered into the spreadsheet in numerical format. In particular, the capability index, merit index 1 and merit index 2 can be generated in this way.

12.4.6 The Design Infringement Matrix

For merit index 3, merit index 4 and merit index 5 the identification and assessment device signified by Figure 12.2 is the design infringement matrix. Its completion in conjunction with the spreadsheet tool again permits these summary index data again to be automatically generated. Figure 12.5 shows a part-completed design infringement matrix. For example 4 × M6 screws require the use of an appropriate Allen key, which represents use of an additional resource (the Allen key) over and above the engagement of the machine operator in completing the



		Resource restrictions						Change element restrictions						Altered sequence restrictions			
Change element (CE) listing		Non-production operator	Single additional resource	Multible additional resource	Non-dedicated additional resource	Obstructed resource	**TOTALS**	Identifiable negative feature or condition	Non-intuitive/non-instructed interfaces	Non-std interfaces for interchange CEs	Full CE removal	Adjustable CE	**TOTALS**	CE must be acted upon in isolation	Always acted upon as a single CE entity	**TOTALS**	**GRAND TOTALS**
⋮				⋮						⋮					⋮		
Change element X	1						1					*	1			0	2_{n2}
M6 × 10 Screw	4		$*_4$				4						0			0	4_{n8}
Top guard	1						0				*		1			0	1_{n2}
Change element Y	2					$*_2$	2						0		$*_2$	2	2_{n4}
Change element Z	10						0		$*_{10}$				10			10	10_{n20}
⋮ Etc.				⋮						⋮ Etc.				⋮			
Totals	–	–	–	–	–	–	–/–	–	–	–	–	–	–/–	–	–	–/–	–/–

Figure 12.5 Example use of the design infringement matrix (partial analysis shown, with the majority of summary totaled data being omitted)

screws' location. The DFC methodology deems this to be a sub-optimal design feature. Figure 12.5 further shows that a top guard change element has to be fully removed during changeover. Once again infringement of optimal design practice is noted and is penalised once the appropriate merit index is generated.

12.4.7 The Concept of a Complexity Quotient

At stage 2 of the methodology, as shown by Figure 12.2, the complexity of the machine needs to be determined. Knowing how many value adding stages there are (the number of distinct and separate ways that the product is altered within the confines of the machine), the user should read the appropriate complexity quotient "*n*" from Table 12.1.

The mechanism of a complexity quotient normalises capability index scores for machines of differing complexity (Boyles 1991). Hence similar capability index scores for significantly different machines suggest similar relative overall improvement potential. An example capability index function for a machine with a complexity quotient of "*n*" = 2 is schematically illustrated as Figure 12.6.

Table 12.1 Determining the value of "*n*" for value adding machines

Value adding stages within the machine under analysis	Complexity quotient "*n*"
1	1
2 to 3	2
4 to 7	3
8 and more	4

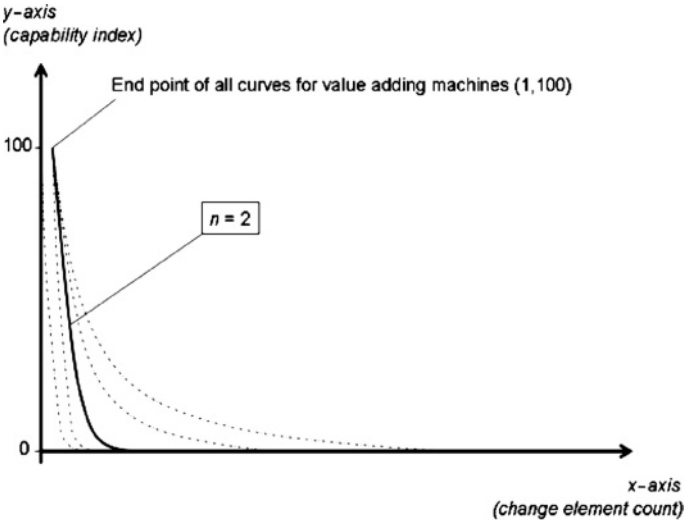


Figure 12.6 Capability index function, value adding machine, complexity quotient "*n*" = 2

12.4.8 Change Drivers

In developing a flexible machine solution a designer needs to be aware how the market for the company's products may change, both imminently and into the future. Hence in assessing change drivers it is being assessed how the company's product ranges, response capabilities and production volumes are likely to alter. This information is critical to being able to decide the changeover specification that the overall manufacturing process has to meet – and hence the changeover capability that constituent machine elements must have. Applicable change drivers and target capability needs to be determined at the outset, during stage 1 of the methodology, as schematically outlined by Figure 12.2. In doing so the index targets at the methodology's decision gates, after stages 5 and 7, are set.

12.4.9 Design Improvement Opportunities

As well as being founded on the concepts described in outline above, the DFC methodology is structured to align with previously determined global opportunities where design can be applied to achieve faster, repeatable, higher quality changeovers (Owen *et al.* 2007):

1. Reduce the number of changeover tasks which need to be completed.
2. Ease completion of the changeover tasks.
3. Enable the changeover task sequence to be altered.

These global expressions of opportunity are task-based and must be translated into a DFC compatible format if a designer is to be able to usefully focus improvement attention. The DFC methodology models changeover as resources acting upon change elements to establish the required new interfaces for each of those change elements. With this perspective of a changeover these global design improvement opportunities can more accessibly be written as:

1. *Global opportunity 1:* reduce the change element count.
2. *Global opportunity 2:* ease restrictions to interface completion.
3. *Global opportunity 3:* ease restrictions that limit when interfaces can be completed.

12.4.9.1 Global Design Opportunity 1

With fewer change elements to act upon less overall work is likely to be necessary.

12.4.9.2 Global Design Opportunity 2

All change element interfaces should ideally be as easy as possible to complete. Poor design can impose restrictions on optimum practice. By simply and consistently analysing restricted resource use and restrictive features of the change elements themselves, the methodology enables the designer to identify specific opportunities to ease interface completion.

12.4.9.3 Global Design Opportunity 3

Shingo's SMED work concentrated strongly on changing the sequence in which tasks are completed (Shingo 1985). In particular he emphasised externalising tasks, although there are also likely to be opportunities to conduct work more in parallel and to diminish occurrences (if more than one person is involved) of staff waiting to be able to commence new tasks (McIntosh *et al.* 2001).

12.4.10 Mapping the DFC Indices and the DFC Design Rules

The DFC methodology's description of global design opportunity is typically not focussed at a level of sufficient detail to provide meaningful assistance to the designer. The methodology addresses this issue by means of the DFC indices and the DFC design rules. Figure 12.7 illustrates how the DFC design rules, the DFC

Global opportunity	DFC Index	DFC design rule (if showing an unacceptable index value)
1	**Capability Index**	Minimise the change element count
	Merit Index 1	Prioritise secondary change element elimination
	Merit Index 2	Sub-prioritise non-value adding change element elimination
2	**Merit Index 3**	Seek operator-executed changeovers (CE interfaces)
		Seek for the to be additional resources +
		If essential, limit additional resources to jus one enbity +
		Dedicate essential additional resources (full availability) +
		Seek unobstructed resource use
	Merit Index 4	By CE design, seek to assist effective resource use
		Seek clear instruction/intuitive interface outcomes
		Seek standard interfaces for sustitutable CEs
		Seek to avoid full change element removal
		Seek elimination of any scope to adus ("right first time")
3	**Merit Index 5**	Seek full independence of interface achievement
		Seek multiple change element entries

+ Note: Any resource (person or tool etc.) other than process operator is an additional resource
[DFC = Design for Changeover, CE = change element]

Figure 12.7 Design opportunity, DFC indices and DFC design rules in full, showing alignment indices and the three identified global opportunities for design-led improvement are aligned. With post-analysis index knowledge, the designer can prioritise where his or her attention is most beneficially directed. Deficient (low) indices are raised, along with a commensurate rise in the machine's changeover capability.

12.4.11 Presenting Summary Information to the Designer

Figure 12.8 shows how summary data has previously been presented to a designer. The numbers will alter as successive design improvement iterations are undertaken. The focus as the design is refined is to raise all DFC indices as far as possible. This is an inevitable outcome as numbers relating to change elements, resources and restriction entries (the latter being taken from the design infringement matrix) are reduced as far as possible.

ANALYSIS ON: Cropping machine – original design
CHANGEOVER TIME: 23 minutes

Value adding stages: 5 Complexity quotient: 3

Change elements:	44	VA $CE_{primary}$:	10
		NVA $CE_{primary}$:	0
		$CE_{secondary}$:	34
Additional resources:	9	Personnel:	1
		Hand tools:	7
		Other:	1
Capability index:	21.7	Merit index 1:	5
		Merit index 2:	100
		Merit index 3:	38
		Merit index 4:	77
		Merit index 5:	68
$\sum$ Restriction entries:	1016	Highest restriction entry:	240

RECOMMENDATION: Radical redesign
MAIN OPPORTUNITIES: $CE_{secondary}$ elimination, adjustment elimination

Figure 12.8 Presentation of summary analysis data

With reference to Figures 12.7 and 12.8, use of the DFC indices in conjunction with the DFC design rules directs the iterative improvement effort. Thus for example merit index 1 might be targeted at the outset to be 75, at which point the design is deemed to be satisfactory. Concentration during the current design iteration could therefore be to "prioritise secondary change element elimination". The summary data of Figure 12.8 can be generated automatically via use of the methodology's previously discussed spreadsheet tool.

12.5 Industrial Validation: A Case of Study

UK Government-supported *lean* consultants, the Manufacturing Advisory Service South West (MAS-SW) are frequently called upon by industry to address changeover losses. Interventions by the MAS are typically of 5 days' duration and frequently employ a specialist changeover training game developed by Lean Games (www.leangames.co.uk). This training game highlights both what can be achieved through better organisation in preparation for the forthcoming changeover (which the authors argue is the primary focus of Shingo's SMED methodology (McIntosh *et al.* 2001) and what can be achieved by better process design. Photographic details of the game are provided on the Lean Games website.

The DFC methodology has been applied to assist designers and other personnel to investigate where design improvement opportunities lie. In its initial embodiment, changeover of the game hardware takes approximately 30 min to complete, with variation being apparent dependent on the skill of the personnel who conduct it. After design improvement opportunities have been identified and pursued (there are fixed opportunities built into the game) the changeover time typically falls below 2 min. The DFC methodology has been employed to assist identification of these opportunities, highlighting where particular problems are apparent in the game, with indices changing as hardware changes are successively undertaken. Access is available to simple spreadsheet programs that allow the respective DFC indices to be calculated automatically upon:

1. input of the complexity quotient;
2. input of the number of change elements of different types present in the proposed design; and
3. completion of the design infringement matrix.

Target index outcomes need to have been defined at the outset of the exercise, which determine when further iterative design (Figures 12.1 and 12.2) is no longer required. As an existing machine is under scrutiny only the second iterative loop, commencing with DFC methodology stage 6 (Figure 12.1), is employed.

12.5.1 A Brief Description of the Game

The game is intended to represent a factory machine. The machine (the game) draws a full curve onto a sheet of paper. The curve's profile is determined by the machine's linkages. The linkages are reset during changeover if an alternative curve profile is required. Turning a handle drives the mechanism, whereby a pen is pulled across the surface of a piece of paper, representing adding value to the product. Another changeover option is to change the colour of the curve, which is achieved by substituting an alternative pen. The position of the curve on the paper is deemed to be critical and requires that the paper is carefully aligned and secured before the handle is turned.

12.5.2 Value Adding Stages

The machine adds value by a pen describing a coloured curve over the paper's surface. One or both the pen or the curve profile can be changed. The machine thus comprises two value adding stages. A full changeover is sought during the exercise, both of the pen and of the curve's profile. The machine has a complexity quotient of 2 (Table 12.1).

12.5.3 Target Indices to Achieve

The exercise facilitator knows the options built into the machine, which enable a sub 2 min changeover to be achieved. Modest index targets are set to enable this performance, post design improvement, to be realised. Most notably a relatively modest capability index score of 40 is targeted. The capability index initially, before design modification is undertaken, is much lower than this (see below) and is raised by reducing the number of change elements in the design (Figure 12.7). The capability index formulae are not here reproduced, but for a value adding machine with a complexity quotient of 2 this target score equates to a reduction in the total number of change elements to 15 or less.

Comparatively modest targets are also set for the merit indices. For example, the DFC methodology penalises the use of resources (including the use of tools) over and above the machine's operator alone completing the changeover. Entries made under the classification of "resource restrictions" (Figure 12.5) reflect infringements of optimum design practice which will lower merit index 3. Knowing what specific restrictions are present, through completion of the design infringement matrix, the designers are able to focus applicable improvement activity. For illustrative purposes improvements which raise merit index 3 are later briefly described. The merit index 3 target is set at 70/100.

12.5.4 Raising the Capability Index

With fewer change elements for resources to act upon there are likely to be fewer tasks comprising the changeover. In its original configuration the game has 53 change elements. These comprise all machine elements which must be acted upon and include substitutable elements where applicable. Notably there are many screws, nuts and washers, each of which must separately be counted. A total of 53 change elements for a value adding machine with a complexity quotient of 2 generate a very low capability index of 4.1/100.

After improvement there are 14 change elements:

1. 2 × pen location catches;
2. on/off switch;
3. 2 × screws;
4. pen holder assembly – existing;
5. substitutable pen holder assembly – replacement, with alternative colour pen;
6. link arm – existing;
7. link arm – replacement;
8. 2 × link arm attachment pins;
9. air pipe;
10. air pipe attachment;
11. USB link – switch.

Although exceeding the target outcome, a resultant capability index of 44.6 tells the designers that there are still appreciably more change elements than would be present in an ideal design. More improvement is thus certainly still possible, driving the capability index yet closer towards 100.

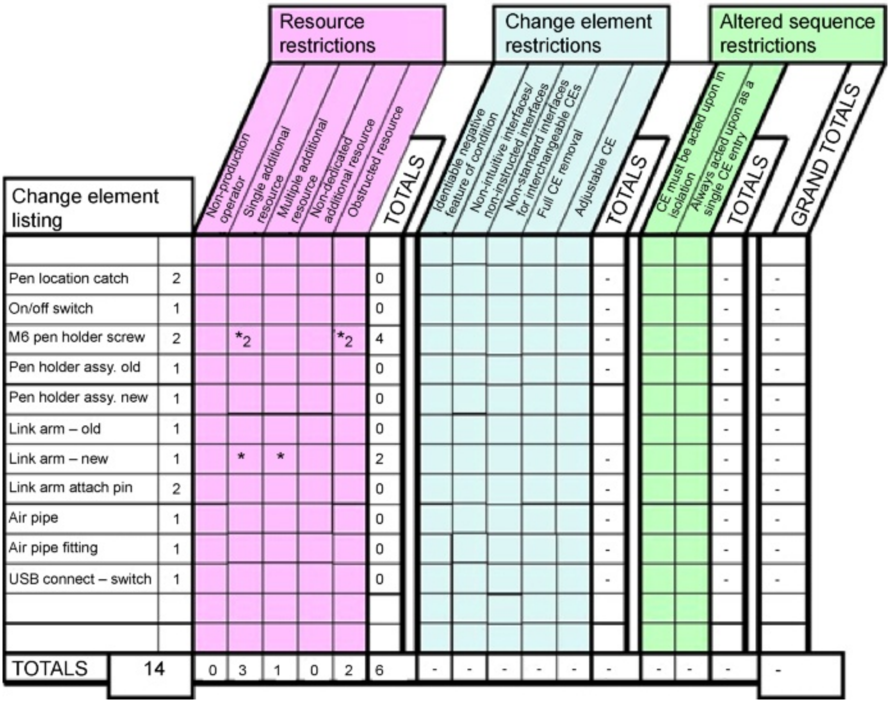
12.5.5 Resource Restrictions – Raising Merit Index 3

Just as there is a focus to reduce the number of change elements, so too the DFC methodology drives a reduction in the resources that are employed beyond engaging just the machine's operator. The methodology seeks for as many changeover activities as possible to be de-skilled, including conducting those activities without a need for separate tools.

Some design improvements for this exercise feature:

1. elimination of the need to use any spanners;
2. elimination of the need to use two hand tools simultaneously;
3. making change elements fully accessible to be acted upon.

Figure 12.9 shows data input to a section of the design infringement matrix with these and other amendments having been made. The predetermined merit index 3 target of 70/100 is comfortably exceeded at 91.4, being derived upon completion of this relevant section of the matrix (91.4 = 100 – (100 × 6/70)). Figure 12.9 further shows how completion of the matrix draws the designer's attention to the explicit flaws that are still present at any stage of the design's evolution. It is seen that in this particular example there is very little further improvement to be found. In the case, however, of further activity to raise the capability index (further design improvement to reduce the total number of change elements in the design) the change element listing would alter and the design infringement matrix, now for these new change elements, would have to be completed afresh.



Change element listing		Resource restrictions						Change element restrictions						Altered sequence restrictions			
		Non-production operator	Single additional resource	Multiple additional resource	Non-dedicated additional resource	Obstructed resource	TOTALS	Identifiable negative feature of condition	Non-intuitive interfaces/ non-instructed interfaces	Non-standard interfaces for interchangeable CEs	Full CE removal	Adjustable CE	TOTALS	CE must be acted upon in isolation	Always acted upon as a single CE entry	TOTALS	GRAND TOTALS
Pen location catch	2						0						-			-	-
On/off switch	1						0						-			-	-
M6 pen holder screw	2		*2			*2	4						-			-	-
Pen holder assy. old	1						0						-			-	-
Pen holder assy. new	1						0									-	-
Link arm – old	1						0									-	-
Link arm – new	1		*	*			2						-			-	-
Link arm attach pin	2						0						-			-	-
Air pipe	1						0						-			-	-
Air pipe fitting	1						0						-			-	-
USB connect – switch	1						0						-			-	-
TOTALS	14	0	3	1	0	2	6	-	-	-	-	-	-	-	-	-	-

Figure 12.9 Completion of the design infringement matrix in relation to the derivation of merit index 3

Post-improvement resources include the continued use of a reference sheet that illustrates how the link arms are to be assembled. A need for this resource could be eliminated in the future by fool-proofing the link arms' orientation, for example, by using different location hole sizes for the respective links. Similarly the use of a transparent check sheet resource is currently retained, whereby the pen-marked sheet of paper (the product) is inspected for image alignment quality. With attention elsewhere given to achieving "right first time" location of all change elements the designers may have the confidence in future to eliminate its use.

12.5.6 Change Element Restrictions – Raising Merit Index 4

Merit index 4 is driven by elimination of sub-optimal design features of the change elements themselves. Improvements undertaken include:

1. elimination of the need for any 'trial and error' adjustment;
2. elimination of a need to fully remove remaining screws (by use of keyhole slots);
3. elimination of previously present torque setting problems.

12.5.7 Altered Sequence Restrictions – Raising Merit Index 5

Merit index 5 is raised by increasing the facility to complete change element interfaces (conduct tasks) at an alternative time. Hence opportunities are being sought to alter the interface completion sequence, to complete interfaces in parallel or to eliminate possible occurrences (for more complicated changeovers) of operator waiting when two or more operators are employed together to complete the changeover.

Implemented improvements include:

1. replicating the pen holder assembly; and
2. acting upon the pen holder assembly during internal time as a single component.

These modifications enable parallel working concerning the pen assembly, or enable the assembly to be built with an alternative colour pen in external time. A penalty is, however, generated in that replicated parts increase the overall change element count, hence lowering the capability index. It is thereby communicated that, notwithstanding when it is undertaken, the total amount of work necessary to complete the changeover rises.

12.5.8 Further Industrial Validation

Application of the methodology has similarly been undertaken *via* a University research associate working on site with an industrial partner. Attention was concentrated on machines used in the manufacture of industrial filters and has resulted in changeover reduction in one instance from over 25 min to under 5 min through design improvement alone. Implementation cost was low, with projected payback occurring in approximately 7 months. The results of further industrial studies are pending, where early results are similarly encouraging.

12.6 Discussion

A leading changeover capability is frequently sought by retrospectively emphasising organisational refinement, seeking to complete tasks both as efficiently as possible and in external time. This though does not represent the only changeover improvement opportunity, where design can alternatively be employed to reduce the number of tasks necessary to conclude the changeover and to make those individual tasks simpler to complete. Ultimately (although not necessarily a sensible goal) changeovers have the potential to be fully automated, being completed, by means of equipment redesign, by an operator throwing a switch. Just one single, simple task remains. For a mass customisation enterprise a leading changeover capability permits highly responsive manufacture between successive product batches with minimum penalty, both in terms of production downtime and deficient product quality. With a mass customisation enterprise typically seeking to present a wide ranging product selection to its customers, this capability can be highly prized.

The current chapter describes how earlier DFC research at the University of Bath has been extended. The use of metrics to guide the designer through iterative improvement is retained, but greater alignment with previously determined high-level design improvement opportunities, such as reducing the number of changeover tasks that need to be conducted, has been sought. The DFC indices and the DFC design rules are both revised and applied accordingly. The DFC methodology is further sought to be unambiguous and repeatable in its use, and this goal has been addressed through the novel modelling of a changeover as the achievement of change element interfaces by the resources that act upon those change elements. Any attempt to break down the changeover into a series of tasks is deliberately avoided, as is the challenge of allocating measurable attributes to those tasks. The measureable attributes of the change elements and resources, as required when applying the DFC methodology, have alternatively demonstrated themselves to be easily determined.

In extending earlier DFC research at the University of Bath the authors argue that greater coherence has been provided to practitioners seeking design-led improvement. Perhaps because of its prominence, Shingo's SMED methodology is sometimes portrayed as a universally applicable tool, more than adequately embracing design as well as organisational refinement opportunity (Cakmakci 2009). The current authors do not share this view, instead recognizing that application of the SMED methodology certainly has its place but arguing that it fails adequately to detail, direct or prioritise what can be achieved through design. The DFC methodology is available to be used alongside the SMED methodology or, for OEM designers, is applicable in place of the SMED methodology.

The authors continue to validate the DFC methodology's use through industrial use trials. In time there may be found to be scope to change the profile of the generic capability index curves, or to weight the penalty applicable when assessing the separate categories of "resource restrictions", "change element restrictions" and "altered sequence restrictions" (Figure 12.8). Again at a later date there is the possibility for other potential users of the methodology, as a community, to access and interactively update such criteria *via* a common database.

12.7 Conclusions

This chapter has given an overview of the field of changeable manufacturing systems and has assessed "changeoverability" from this perspective, which Nyhuis *et al.* (2006) describe as "the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment with minimal effort and delay". Equally, Wiendahl and Heger (2003) propose "changeability has become a decisive factor in the competitiveness of manufacturing companies in addition to the classical target factors of cost, time and quality". Uncertainties influence today's manufacturing environment more than ever, for example due to increasing customer demand for product variety, and modern manufacturing paradigms share a fundamental aim to enhance the ability of manufacturing systems to react quickly to such uncertainty. Collectively a need for high levels of inherent system "changeoverability" through changeover-focused design of equipment is identified. Change drivers have been outlined, and their role when specifying the changeover capability of new equipment has been briefly described. The authors have outlined the University of Bath's metric-driven DFC methodology. It addresses three identified global opportunities where improved machine design can impact upon changeover capability. Further, it has been founded on the premise that changeover tasks need not be explicitly evaluated and that index-generating data should be both simply and unambiguously determined. The methodology has initially been validated through protracted research collaboration with an industrial partner and, additionally, in conjunction with the changeover offering of a vendor of lean industrial games.

Space restrictions necessarily limit what can here be described, including derivation of the DFC indices, which reflect the competence of various aspects of the overall design. Only a summary of work completed to date is presented, where omissions that are necessarily dictated by lack of space may perhaps hinder understanding of what is involved. Contact with the authors is invited to gain further details, for example, of the theory upon which the DFC methodology is built, as well as greater in-depth understanding of its application across varied case study situations.

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Chapter 13
Additive Manufacturing for Mass Customization

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Abstract Additive manufacturing (AM) is a disruptive manufacturing technology that requires no tooling for production. AM requires three dimensional computer aided design (3DCAD) data in order to *additively* build parts from numerous materials, including polymers, metals and ceramics. Within this chapter the advantages realized by taking an AM approach are considered as well as their application in mass customization MC). Particular emphasis is given to the use of AM in the production of customer generated data from a number of sources including massively multiplayer online role-play games (MMORPG).

Abbreviations

3DCAD	Three-dimensional computer aided design
3DP	Three-dimensional printing
AM	Additive manufacturing
CAD	Computer aided design
CEO	Chief executive officer
CNC	Computer numerical controlled
DFM	Design for manufacture
FDM	Fused deposition modeling
HVAC	Heating and environmental ventilation control
IP	Internet protocol
ITE	In-the-ear
LS	Laser sintering
MC	Mass customization
MMORPG	Massively multiplayer online role-play games
MPH	Mobile parts hospital
PC	Personal computer
SL	Stereolithography
STL	Standard template library
USB	Universal serial bus
WoW	World-of-Warcraft

13.1 Introduction and Background

Customization and, particularly, MC (Pine *et al.* 2000), has received a great deal of attention in recent years as a method of creating increased value for manufacturers and retailers alike. Many instances of mass customization (MC) use innovative supply chain concepts to produce customized products from a range of existing "modules" (Salvador *et al.* 2002). These modules are often manufactured using traditional manufacturing processes and therefore require investment in tooling. The cost of tooling, *i.e.,* for injection molding, pre-determines the necessary component volumes in order to manufacture parts cost-effectively. Consequently, this may prohibit new product development and therefore stifle innovation in product development, particularly for bespoke or tailored products. In addition, the ability to produce components that fit customer needs intrinsically means that the customer is intimately involved in the product design process. This chapter provides an example of the marriage between personalization and a method of production that does not require tooling investment. The chapter will present a short background on the manufacturing technology, known as AM followed by its uses and advantages. Finally, a novel concept in MC utilizing AM systems will be shown as an example for the technology, namely the production of bespoke online gaming characters.

Additive Manufacturing

AM, often known as rapid manufacturing, direct digital manufacturing and e-manufacturing amongst many others, encompasses a number of process technologies. Examples of AM include: stereolithography (SL), laser sintering (LS), fused deposition modeling (FDM), and three-dimensional printing (3DP). Although each of these processes is different, they encompass the same process philosophy. AM produces components in an additive fashion, where components are fabricated by adding successive layers of material together, driven by 3DCAD data. This contradicts traditional manufacturing techniques, such as subtractive (machining) and formative (molding) methods. AM has been defined as the production of parts or final products directly from digital data, eliminating all tools (Dekker *et al.* 2003, Tuck and Hague 2006).

From a manufacturing and marketing perspective, there are several advantages in adopting an AM approach. Firstly, design freedom (Hague *et al.* 2003); designers are free to design complex geometries that only AM machines are able to fabricate. The direct fabrication of these parts from CAD data also means that the tooling step is eliminated, hence, designers do not have to be concerned about many design for manufacture (DFM) criteria; for example, whether a geometry can be removed from a tool cavity. Additionally, due to these design freedoms, assembly operations required to make up a component that lead to an increased cost to the consumer, especially for low volume and custom components, can be reduced. Removing tooling means that changes to the design can be made quickly without significant effect on cost. At the same time, the long lead time for the delivery of tooling can be avoided, shortening the time-to-market of a product (Hopkinson and Dickens 2003). The removal of tooling has further advantages; without tooling, it is possible to fabricate parts and products in small quantities, which would not otherwise be economically viable. AM enables low volume production at a more economical cost, as shown by Ruffo *et al.* (2006). Without the cost of tooling, the cost of low volume production by AM can be significantly lower when compared to traditional manufacturing processes. Numerous studies have been carried out to discern the differences in costs between AM and traditional manufacturing techniques, selected references include work by Hopkinson and Dickens (2001) and Ruffo *et al.* (2006).

AM is a disruptive technology that holds promise in the development of MC in particular for complex and/or body fitted components where geometry is particularly important. However, as with many technologies it is necessary to understand the underlying benefits and investments required for such technology to exist in today's manufacturing enterprises. The benefits discussed above are linked to the potential geometric complexity afforded by the technology and the removal of tooling from manufacture. The technical investments necessary to carry out AM are not too different from many other modern production technologies, for example CNC machining. The precursor to any AM produced component is a 3DCAD model of the item, normally in the format of an. STL file, a common option on commercial CAD packages. The file is then positioned and placed in the "build envelope" by a skilled technician. This build packet is then uploaded to the primed AM machine where the parts are built autonomously. After the machine has completed the build process the parts are removed and post-processed to remove any extraneous materials or supports. The level of investment required to enable an AM manufacturing facility is a function of the manufacturing technology being used; this can vary from a few thousand dollars to many US $100's of thousands with associated differences in the necessary infrastructure required. Labor requirements *during the process* are low. However, skilled labor is required to setup the build files and orient the parts in the virtual build envelope and set up the machine for manufacture. Following manufacture, the parts need to be "cleaned up" ready for the customer, which may include coating or other surface treatments.

AM has already been adopted in several industries, including in-the-ear (ITE) hearing aids (Dickens *et al.* 2005; Wohlers 2003), automotive (Tromans 2006, Kochan 2003) and aeronautical industries (Amato 2003), for the production of some parts. Major hearing aid companies have adopted AM as their mainstream production technique for ITE hearing aids. Siemens Hearing Instruments has been producing customized ITE hearing aids using AM techniques at a production rate of 2000 pieces *per* week (Masters *et al.* 2006). Traditionally, the manufacture of ITE devices required a great deal of skilled labor in the production of the customized hearing aid shell, and was thus dependent on the abilities of the technician undertaking the work. The introduction of CAD technology and particularly the use of three-dimensional scanning methods have enabled much of this design process to be digitized. An audiologist, using wax-like materials, takes a physical impression of the outer ear; digital information is captured using a non-contact 3D scanner, either at the audiologist or at the manufacturer. It is important at this stage to get good and accurate data as this will determine the fit of the ITE device, which directly impacts on the ITEs in-service performance. The scanned data is then processed into a suitable CAD file and the necessary operations for accommodating the electronics carried out. The final shell is then sent to an AM machine (commonly, SLA or the Envisiontec Perfactory process) and the final shell fitted with the electronics and sent to the consumer. This method has greatly reduced the uncertainties in producing a custom-fitting item, yielding a greater degree of consistency in the product.

In the aeronautical industry, heating and environmental ventilation control (HVAC) systems inside fighter jets are printed out by AM machines, and have led to savings and reductions in cost and production schedules of about 50%. In other defense applications, the US military has set up a mobile parts hospital (MPH) at sites in Kuwait and Iraq, printing replacement parts for damaged equipment. The army is able to replace broken parts within hours instead of waiting days or weeks for the new replacement (Aston 2005). Besides industrial usage, AM has also been adopted in consumer products. MGX, a division of Materialise of Belgium, has been using AM technology for the fabrication of customized and limited edition lamps with complex designs (MGX, 2007).

The availability of customization has been possible with advances in manufacturing technology, enabling low volume production to be achieved efficiently. AM is envisaged to be the enabler for many types of customization (Tuck and Hague 2006, Dickens *et al.* 2005). As discussed earlier, the development of tool-less production enabled by AM makes it economically viable for small volume production. As such AM would be suited to cater for niche markets requiring unique end products. This fits well with the requirements of customization, which manufactures a product or delivers a service in response to a particular customer's needs (Pine *et al.* 2000). This in turn means producing a one-off item. With a greater degree of design freedom, AM is potentially able to cater to almost any geometric requirements.

As we have already seen, AM has found a number of MC uses, ranging from small volume applications such as the MPH to high volume applications such as ITE hearing aids. However, in all these cases, the geometric data used to drive the AM process has been captured using secondary scanning technologies and expert systems software. For the true MC potential of AM to be fully exploited, the technology must be coupled with consumer driven or "enabling" software, that is capable of producing high quality data.

At present most 3DCAD systems are beyond the capabilities of the untrained user. However, both online design tools and design tools embedded into computer games have already been developed to be used with no formal tuition beyond the on-line help page. It is this freedom of user generated content that has enabled a small but growing number of companies to exploit the MC freedoms of AM by coupling the technology with both simple internet based design applications and interactive computer games packages.

13.2 AM and the Realization of Mass Customized Internet Content

Although the consumer has been able to purchase AM products online for a number of years from companies such as Freedom of Creation and Materialize MGX, it is only since mid 2006 that the consumer has been able to engage in the actual design process, using web based tools, prior to the delivery of their tangible AM product.

Probably the earliest example of using AM to enable the manufacture of online "consumer described" content was the launch of www.fabjectory.com by Mike Buckbee in 2006 (Fabjectory Website 2009). The Fabjectory business model enables players from the Metaverse "Second Life" to purchase models of their individually designed avatar characters manufactured using Z-Corporation 3D-printing. Unlike other MMORPGs, the creators of Second Life, Linden Laboratories of San Francisco USA, have assigned all intellectual property rights for characters, building and vehicles to the game's user (Wagner 2008). This, in essence, gives the estimated one million Second Life "active residents" the right to exploit their own designs. This has led to a number of interesting business cases, where real-world clothing brands have been developed based on virtual world designs. Moreover, this also allows every Second Life user to extract the geometric and render data of their individual avatar characters and provide this to Fabjectory for 3D printing, without any infringement of Linden Laboratories intellectual property. On the other hand, this also represents the weakness in the Fabjectory business model. As Fabjectory retains no control of the 3D data enabling the AM supply chain, any "secondlifer" can extract their own data and send this to be printed by their local 3DP service provider.

To close this loop hole in lost revenue, the first truly integrated online AM fulfillment business was launched in Singapore in early 2007 by Genometri PTE Ltd., a spin-off company from the National University of Singapore. Trading under the brand name Jujups (www.jujups.com) the company has developed an interactive 3D design "portal" that allows web users to design a range of simple "giftware" products such as photo frames, key fobs, tokens, USB flash drive casings and personalised Christmas decorations. The resulting designs are then additively manufactured using a Z-Corporation full color 3D printing system before being dispatched directly to the customer.

According to Genometri CEO Sivam Krish the system uses a series of simple web based JavaScript design tools. This allows users to select from a pallet of 3D objects. Examples include picture frames that can be personalized with text, relief objects such as flowers, or with photo images uploaded directly by the user from the home PC or laptop. On completion the "virtual design" can be saved and shared with others or committed to print, at which point payment is made by credit card. As a closed loop system, all resulting 3D data remains within the Genometri Ltd. fulfillment model and as such cannot be extracted and printed by an external third party. Interestingly, Genometri does not own its own AM hardware, but relies on a network of 3D printing service bureaus located in Asia, the USA, and Europe. This concept of distributed additive manufacturing will be discussed later.

A similar closed loop AM fulfillment model to Jujups has been developed by the 3D Outlook Corporation in the USA, where users are able to select topographic data of the earth's surface online, and use this as the basis for a three-dimensional color relief map printed in a selection of sizes. Figure 13.1 shows how the technology has been used to create a three-dimensional relief map of the Grand Canyon.

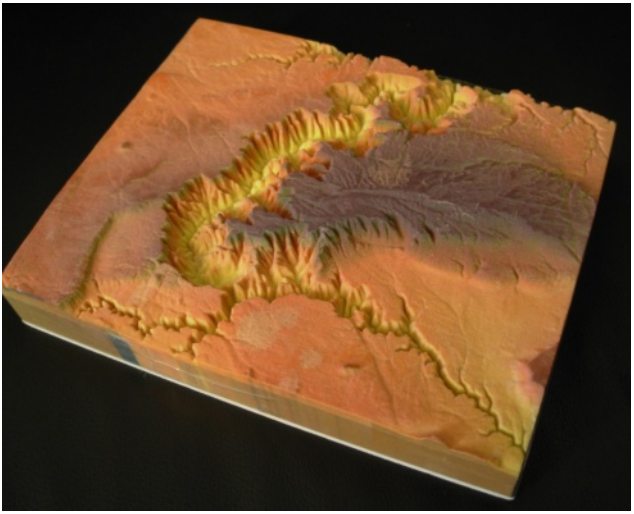

Figure 13.1 3D printed topographic representation of the Grand Canyon (copyright Econolyst Ltd.)

The system uses a JavaScript web interface (www.landprints.com), (Landprints Website 2009), which is linked to the US geographic survey mapping database of the contiguous United States. Users first select the area they are interested in printing, using a "Google-earth" style application, which can be rotated and zoomed. Once selected, the two- dimensional topography including roads, rivers, and lakes can be given an exaggerated or to-scale three-dimensional depth, using an online *Z*-axis height slider. Once the height of the model is selected, the user decides on the model size with options of 5", 6", and 8". A credit card payment is then taken of between US $37.95 and US $69.95, with delivery guaranteed within 2 weeks. The offer is currently aimed at town planners, councils, architects, and development site owners. However, there are also plans to allow users to upload their own topological data or imagery in the future.

Although websites such as Jujups, Landprints, and Fabjectory have identified and exploited possible mass customization applications for AM, they appear to be constrained in their marketing channels to the internet, possibly with the exception of Landprints who could advertise in trade journals. An alternative methodology of engaging the consumer with MC AM is to integrate the technology with an existing software package such as a PC based computer game or web based MMORPG.

13.3 The Integration of Additive Manufacturing with Computer Games

The first fully integrated AM business model within the computer games industry was launched in December 2007 by US business start-up FigurePrints (www.figureprints.com), (Figureprints Website 2009). FigurePrints is an exclusive licensing partnership between a former Microsoft executive, Ed Fries, and global software house Blizzard entertainment. The FigurePrints website allows players of the MMORPG World-of-Warcraft (WoW) to order 1/16th scale models of their online gaming character, manufactured using full color AM. However, unlike Second Life where the character IP resides with the designer, all WoW character definitions remain the exclusive intellectual property of Blizzard entertainment, albeit they are designed using a suite of “character building tools” by the games players. Hence, FigurePrints provides a previously unimaginable licensing opportunity for Blizzard and a means for emotive gamers to realise on screen characters in real life. By March 2008 FigurePrints had received over 100,000 enquiries for characters costing US $140 each (Wohlers 2008). By December 2008 these orders were being fulfilled using six in-house Z-Corporation Z510 color 3D printing machines. However, demand still appears to far outweigh supply, with order fulfillment being based on a monthly lottery system governed by the companies’ capacity to produce a maximum of 1,700 characters *per* month (as at December 2008).

Although it is possible for anyone with knowledge to extract WoW characters from the model viewing software, as shown in Figure 13.2, and to re-render this using commonly available software such as 3D Studio Max, this would be considered a breach of Blizzard Entertainment’s copyright if the parts were ever sold, and as such will prevent any commercial competition to FigurePrints within the near future.

Figure 13.2 World of Warcraft model printed using Z-Corp 3DP (copyright Econolyst Ltd.)

It should be noted that WoW currently has 11 million registered players. Hence FigurePrints current penetration represents less than 1% of the potential market by enquiries, and a fraction of 1% in terms of paying customers. Nevertheless, based on the current limited production capacity the business still has the capability to turnover in-excess of US $2.85 million *per annum*.

Following the rapid and somewhat unexpected success of FigurePrints, AM technology vendor Z-Corporation of Massachusetts USA (www.z-corp.com) have now established their own 3D printing service "Z-Prints" to service the online and platform computer gaming sectors. To date the company has 3D printing agreements to support the computer games "Rock Band" (www.rockband.com/merch), (Rockband Website 2009) and "Spore" (www.sporesculptor.com), (Spore Website 2009), both published by global games leader Electronic Arts (EA). A typical 3D printed Spore character, which would cost US $49.95, is shown in Figure 13.3; this compares to a WoW FigurePrint costing US $140.

Interestingly, in addition to purchase price there is also a question of "emotional value" when considering the cost of 3D AM games characters or avatars. Spore and Rock Band characters, although fully defined by the games players, could have a limited emotional attachment for the gamer, as they are easy to design and modify and therefore easily re-created. This poses the question:

> *Do I really feel emotionally attached enough to my games character to part with hard cash just to see it printed out?*

Figure 13.3 EA Games, Spore character printed using rapid manufacturing (copyright Econolyst Ltd.)

This differs greatly from FigurePrints where WoW gamers often play the same character for many hundreds if not thousands of hours, building up an emotional bond that may drive the gamer more towards the purchase of a tangible avatar. Research by Wolfendale (2007) suggests that MMORPG players can develop a form of "avatar attachment", where the avatar becomes an extension of the gamers' persona. To have a tangible 3D representation of this persona is therefore a natural expression of personal vanity, very much like a photograph of your latest skiing holiday or a family portrait. It is this level of avatar attachment that may in the future be the driver behind successful computer games enabled AM business.

Within both Rock Band and Spore, gamers have the option to design their own characters, prior to committing to a 3D print. At no stage, however, does the gamer gain access to the 3D geometric or render data, as this is passed only between the software and Z-Corp, ensuring that models cannot be printed externally, which would lose revenue for both Z-Corp and EA. Unlike FigurePrints, the Z-Corp business model works on a traditional order and fulfillment principle, with parts being manufactured following order for immediate dispatch. The costs of 3D characters produced by Z-Corp are also noticeably lower than other online offerings such as FigurePrints, although they are slightly larger. This appears to be a function of the models being manufactured on lower resolution, lower cost machines, but it can also be assumed that Z-Corp are using their own 3D printing machines and materials supplied nearer to cost price.

13.4 Poachers and Gamekeepers

The result of an AM technology vendor becoming a service provider poses a significant challenge for other businesses wishing to operate in this domain, as it is difficult to see how anyone can compete in price against a business that also controls the machine, maintenance, and material supply channels of its competitors. However, the Z-Corporation business model may have some weaknesses if it is to support truly globalised AM product customization.

At present Z-Corp has opted for a "centralized factory" configuration, with all 3D printing capacity located under one roof in Massachusetts. Although a cost effective methodology for supporting the North American market, it may be limited when trying to supply the entire potential consumers base, as almost all computer games are now sold on a global basis. One of the most significant limitations is postage and packaging costs. Z-Corp models are relatively fragile and require careful packaging prior to shipping. Hence, many fine feature games character models are initially placed under a glass or Perspex dome and glued to a rigid base. This can result in relatively high shipping costs as a percentage of the product value. Moreover, using this centralized production model, lead-times between product order and fulfillment are increased relative to the length of the transportation phase between the customer and the Massachusetts based production facility.

Of course, the alternative is to locate manufacture nearer to the consumer. However, traditional supply chains have resisted this notion as it requires expensive duplication of fixed assets such as injection mold tooling, jigs, fixtures, and specialist production equipment. For example, a typical injection molding tool for a small games character could cost in the order of US $5,000. Hence, if production were required in four different locations, US $20,000 of tooling would be needed. Moreover, this tooling would only be able to make a single product design. Hence, the production model would be one based on mass production to amortize the tool investment. With AM, however, there is no need for such capital investment in tooling, as the technology operates independently and discreetly. Still, there is an initial investment in the 3D printing technology, which can cost between US $45K for a color Z-Corporation printer, up to US $500K for a high throughput polymeric laser sintering system. But this is no different to the investment needed in, for example, the injection molding machine. However, the AM technology is then capable of producing an infinite variety of different products without additional capital investment. Hence, AM can be used to make the same part or multiple versions of a part at multiple locations with no additional cost.

This concept of "distributed additive manufacture" is currently being developed by one of the authors for the production of computer games characters and other additive manufactured products under the brand www.per-snickety.com (Per-snickety 2009). Per-snickety uses a networked approach to distributed manufacture. The Per-Snickety concept is based around a centralized "print-queue", which is feed by multiple data sources, such as computer games, online design orientated websites or simply by companies looking to source AM models. The print queue is then accessible only to validated Per-snickety print partners, who can then download complete platforms of work to place on their machines for a pre-agreed price. The Per-snickety concept is to use underutilised machine capacity on Z-Corp 3DP machines and polymeric laser sintering machines. Upon completion the AM parts are shipped directly to the consumer by the Per-snickety print partner.

It is hoped that as global demand for Per-Snickety increases, so part files in the print queue will be automatically routed to the closest available machine to the consumer, reducing shipping costs and the carbon footprint of the entire supply chain.

13.5 The Future

Although they are still in their infancy, centralized and globally distributed AM supply chains could be a short lived phenomenon as home based additive technologies become a commercial reality. Pasadena based Desktop Factory (www.desktopfactory.com) are close to launching a sub-US $5,000 polymeric based additive technology that will be in offices in 2010 and could be in homes as early as 2012. The system, which is shown in Figure 13.4, does have its limitations, as it can only produce relative small (4" × 4" × 4") models in a single color.

Figure 13.4 Beta test version of desk top factory low cost AM machine (copyright Econolyst Ltd.)

However, it is not inconceivable to imagine the technology both reducing in price and increasing in functionality with the addition of color and an increased build envelop. AM of MC internet design and computer games characters could then become as common as the home printing of photographs, or the playing of downloaded music or video media. In the future we could be in a position to download and 3D print new product designs, or as shown, engage in part of the design process prior to purchasing our design for home based digital fabrication.

But we must not lose sight of the data originators in this future supply chain and their brand identity, as this is key to any company engaged in both virtual or tangible product design and realization. Where the end user can manipulate a design, brand control becomes paramount, as without sufficient safety measures the end-user could in effect destroy the brand through the creation of poor quality design. Within AM, this could be manifested in the user designing a product, such as a computer games character or avatar, which is too detailed for the AM process, resulting in a part with missing features and a poor perceived quality, hence impinging the quality of the brand. One solution would be the “free issue” of data to users with the caveat “print at your own risk”. However, this would require the release of core intellectual property data including both the geometric and color information relating to the design. Even based on a “pay-to-download” business model, this would in effect allow the user access to make multiple copies of their design with no ongoing revenue to the data provider. Other considerations include health and safety, product liability, and recyclability.

13.6 Implications of AM for MC Businesses and Future Research

The implications of AM on the potential of MC businesses that deal in physical products, particularly those that have significant consumer geometry or generated content are profound. The overarching benefits of taking an AM approach to manufacture lie in the removal of tooling from the manufacture of the physical product. The connotations of removing this tooling are potentially profound as it removes restrictions throughout the product development and production process. Previous work has shown the potential for AM to significantly change paradigms for design, production, and supply chains.

The amalgamation of customized content, whether it is user-generated or user-specific, with AM has enabled the successful manufacture of numerous products in very disparate markets, *i.e.*, from the computer gaming market to the medical arena. This potential to affect different markets with a single manufacturing technology genre is rare and requires further investigation by both the academic and business communities. Aspects such as the enabling of consumer co-design and use of customer data (Campbell *et al.* 2003), the implications on custom fitting products (Custom Fit 2009) are all being targeted by practitioners of the technology. In addition, work has begun on other aspects of AM particularly in the implications to business and supply chains. Recent work by Tuck *et al.* (2007) has discussed the potential implications for AM on supply chain methodologies and practices. Discussing the potential effects of AM on traditional supply chain methodologies, a number of benefits could be attributed to existing supply chain management practices such as lean, agile, and Postponement. In brief, the ability to make what you want when you want and where you want it has profound impact on the types of methodologies that can be developed for MC applications. AM is an inherently agile process requiring little in the terms of setup to produce different parts. In addition, these different geometries can be potentially built at the same time, on the same machine platform. This has an obvious impact on the practice of modularization (Salvador *et al.* 2002). Though not superseding the practice of modularization, AM may be able to facilitate the modularization activity in a different way. The ability to hold stock as digital data and print on demand has potential for manufacturing the modular components commonly used for MC on demand. This could potentially push postponement points further downstream enabling the supply chain to become leaner upstream and pushing the customization downstream, potentially to the retailer or even the consumer.

13.7 Summing Up

In conclusion, AM holds a great deal of promise for the MC community. The additive manufacture of mass customized computer games and internet content has been an exciting example, coming from nowhere to a multi-million dollar industry almost within months, let alone years. Much of this is due to the low barriers to entry, but also the ability to provide the consumer with something they have never had before, a tangible way to turn computer designs into mass customized 3D products. However, these supply chains are not simple, as they rely on finding a common ground where the consumer, the games developer, and the 3D printer are all winners.

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Chapter 14

Selecting Relevant Clustering Variables in Mass Customization Scenarios Characterized by Workers' Learning

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Abstract Clustering is an important technique in highly customized production environments, where a large variety of product models is typical. It allows product models with similar processing needs to be aggregated into families, increasing the efficiency of production programming and resources allocation. The quality of the clustering results, however, relies on using a set of relevant clustering variables. Our method selects the best clustering variables aimed at grouping customized product models in families. There are two groups of clustering variables: those generated by expert assessment on the features of products and those predicting the workers' learning rate, obtained by means of learning curve modeling. The method integrates an elimination procedure with a *k*-means clustering technique. The method is illustrated on a shoe manufacturing process.

Abbreviations

LC	Learning curve
MV	Model variables
SI	Silhouette index
SV	Specialists' variables

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14.1 Introduction and Background

Mass customization environments assume the manufacturing of a large variety of customer guided product models with reduced lot size. Although products may differ in terms of complexity and specific features, they usually require similar machinery and manual processing (Da Silveira *et al.* 2001). In that context, the clustering of models in families with analogous characteristics may enable a more efficient production programming and resource allocation of mass customized production systems.

Clustering tools have been widely used to assign observations (*i.e.*, product models) with similar characteristics to groups (see Jobson 1992, Kaufman and Rousseeuw 2005). Observations allocated in a group are similar to others also in the group and different from those allocated in other groups, without loss of information about the groups (Hair *et al.* 1995). In customized environments, product characteristics (*e.g.*, product complexity, number of operations and parts) have been traditionally used as clustering variables (see Anzanello and Fogliatto 2007). That generalizes information from existing product models to new ones.

In manual-based production environments, the use of clustering variables exclusively related to product characteristics may lead to unsatisfactory assignment of products to families. The way workers adapt themselves to the requirements of a new model should also be included in the clustering procedure. More specifically, the rate at which workers learn the required procedures could provide valuable information about the model's complexity (Uzumeri and Nembhard 1998, Nembhard and Uzumeri 2000), enabling a better assignment of that model to a family. Workers' learning rate can be efficiently estimated by means of learning curve (LC) modeling and then incorporated into the clustering procedure as variables.

The use of many clustering variables, however, may undermine the grouping procedure. As suggested by authors such as Milligan (1989) and Brusco and Cradit (2001), only a limited subset of variables is effectively relevant to establish the cluster structure. The use of irrelevant variables reduces the precision of clustering algorithms, due to the assignment of observations to improper clusters. In that context, selecting the most relevant clustering variables becomes a mandatory step to ensure the formation of consistent families of products.

The sections that follow present an iterative method to select the best clustering variables aimed at assigning customized product models to families with similar characteristics. Clustering variables are chosen from a combination of two groups of variables: (1) those generated by expert assessment on the complexity and features of existing products, and (2) those predicting the workers' learning rate when executing tasks on a new product, obtained by means of LC modeling of data collected from assembly procedures on similar products. The most relevant variables are identified by combining a "leave one variable out at a time" procedure with a k-means clustering technique. The clustering performance is evaluated by means of a silhouette index (SI), which indicates the variable to be removed. This iterative process is repeated until a lower bound of remaining variables is achieved, and a graph relating SI and number of remaining variables is generated. The maximum value of SI in that graph identifies the clustering variables to be used in future clustering procedures.

We also address a major pitfall of cluster analyses, namely: how many clusters should be formed? For that matter, the iterative process described above is replicated for a reasonable range of numbers of clusters. The maximum SI for that range identifies the ideal number of clusters.

We illustrate the proposed method in a shoe manufacturing application. We demonstrate that a reduced set of variables, consisting of both experts opinions on product features and LC parameters, leads to the best grouping performance. We also demonstrate that the clustering quality achieved by the selected variables is significantly higher than that obtained by using expert assessed variables alone.

We now provide a brief review of selected LC models, the *k*-means clustering technique, and the fundamentals of SI.

14.1.1 Learning Curves

LCs are mathematical representations of a worker's performance when submitted to a manual task repeatedly. Workers require less time to perform a task as repetitions take place, either due to familiarity with the task and tools required to perform it or because shortcuts to task completion are discovered (Teplitz 1991). There are several LC models proposed in the literature; most notably (1) power models, such as Wright's, (2) hyperbolic models, and (3) exponential models.

Wright's model is the best known LC function in the literature, mostly due to its simplicity and efficiency in describing empirical data. The curve is represented by

$$t = C_1 z^b , \tag{14.1}$$

where z represents the number of units produced, t denotes the average accumulated time (or cost) to produce z units, C_1 is the time (or cost) to produce the first unit, and b is the slope of the curve, such that $-1 \leq b \leq 0$ (Wright 1936). The parameter b can be assumed as the learning rate parameter, measuring how fast a worker becomes familiar with a new task or product model. For further discussion on b, refer to Jaber (2006) and Jaber and Guiffrida (2007).

Hyperbolic and exponential LC models enable a more precise description of the learning process if compared to Wright's model. The three-parameter hyperbolic model, reported by Mazur and Hastie (1978), is given by

$$y = \frac{m(x+p)}{(x+p+r)} \tag{14.2}$$

with $p+r>0$. In (14.2), y describes worker's performance in terms of units produced after x time units of operation ($y \geq 0$ and $x \geq 0$), m gives the upper limit of

y ($m \geq 0$), p denotes previous experience in the task, given in time units ($p \geq 0$), and r is the learning rate parameter measured in time units demanded to reach $m/2$ (*i.e.*, half the maximum performance).

Uzumeri and Nembhard (1998) and Nembhard and Uzumeri (2000) modeled performance data from a population of workers exposed to new tasks using the hyperbolic model. The parameters in (14.2) were analyzed to determine workers' learning profiles. Results indicated that fast learners (workers whose LCs had low values of r) presented performance limits (m values) lower than those presented by slow learners (workers with high values of r). The authors recommended the assignment of fast learners to tasks with shorter production cycles, and *vice versa*. In customized environments, which are characterized by short production runs, workers (or teams of workers) associated to low values of r should be prioritized. The parameter m, which describes workers' final performance, is not important in mass customization settings since the number of repetitions in a production run is seldom enough to achieve that level.

One of the most important exponential LC models is the three-parameter model, which is presented in (14.3). Parameters of this model have the same meaning as those of the hyperbolic model,

$$y = m(1 - \exp^{-(x+p)/r}) \tag{14.3}$$

Knecht's model, which is represented in (14.4), is recommended for long production runs, where the learning parameter can present modifications as repetitions take place (Knecht 1974, Nembhard and Uzumeri 2000). The parameters are also as described before.

$$y = \frac{C_1 x^{b+1}}{(1+b)} \tag{14.4}$$

Although learning parameters in (14.1)–(14.4) assume different notations (*i.e.*, b and r) and magnitudes, they are equivalent in representing workers' learning rate and will be addressed as identical through our method.

14.1.2 Clustering Analysis and the Silhouette Index

Data clustering is a widely known multivariate analysis technique that inserts observations (objects) of a population into clusters (groups), such that observations within the same cluster have a high degree of similarity, while observations inserted in different clusters have a high degree of dissimilarity (Jobson 1992, Hair *et al.* 1995, Kaufman and Rousseeuw 2005). Clustering methods have been applied in many areas such as pattern recognition, decision making, and reliability analysis, among others (Taboada and Coit 2007).

There are two main branches of clustering algorithms: non-hierarchical and hierarchical methods. The most popular non-hierarchical clustering method is the *k*-means clustering algorithm, which is widely recognized for its efficiency in grouping observations from datasets (Jain and Dubes 1988).

The *k*-means algorithm inserts each observation into the cluster with the closest centroid. The centroid for each cluster may be calculated or randomly defined by the *k*-means algorithm. The objective function f to be optimized by the *k*-means algorithm is (Taboada and Coit 2008):

$$f = \sum_{j=1}^{n} \min_{i \in \{1,\ldots,k\}} \| \mathbf{v}_j - \mathbf{c}_i \|^2 \tag{14.5}$$

where $\mathbf{v}_j$ is the jth data vector, $\mathbf{c}_i$ is the ith cluster centroid, k is the number of clusters to be formed, n is the total number of vectors of observations, and ||•|| is the norm operator. The number of clusters k is defined by the analyst.

A graphical display, named silhouette graph, evaluates the performance of the clustering procedure by measuring how similar an observation is to observations in its own cluster compared to observations in other clusters (Kaufman and Rousseeuw 2005). An SI that ranges from +1 to –1 is associated to each observation j. A value close to +1 identifies observations that are distant from neighboring clusters (*i.e.*, were properly assigned to a cluster); SI_j close to 0 denotes observations that do not clearly belong to one cluster or another; and SI_j close to –1 indicates observations that were probably allocated in the wrong cluster. SI_j is estimated as in (14.6).

$$SI_j = \frac{b(j) - a(j)}{\max\{b(j), a(j)\}} \tag{14.6}$$

where $a(j)$ is defined as the average distance from the jth observation to all the other observations belonging to j's cluster, and $b(j)$ is the average distance from the jth observation to all the observations assigned to the nearest neighbor cluster. Euclidean or Manhattan distances are normally used to calculated distance between observations.

The global quality of a clustering procedure can be assessed by averaging SI over the n clustered observations. It is important to mention that SI is independent of the clustering technique. Moreover, Rousseeuw (1987) and Rousseeuw *et al.* (1989) suggest that the SI can be used to determine the best value of k (*i.e.*, the number of clusters).

Finally, a major problem in cluster analysis is the selection of variables that truly define clusters with distinct characteristics. Studies have suggested that only a limited subset of variables is effectively important in defining the cluster structure (Fowlkes *et al.* 1988, Milligan 1989, Gnanadesikan *et al.* 1995, Brusco and Cradit 2001), and several approaches have been proposed to select the most relevant variables. The incorporation of irrelevant clustering variables may lead to inaccurate assignments of observations to clusters, in both hierarchical and non-hierarchical cluster analyses (Milligan 1980, 1989).

14.2 Method

The method to select the best variables for clustering purposes relies on two operational steps. In the first step we define the two groups of clustering variables to be used. The first group is subjectively defined based on production staff's expertise, and describe assembly complexity and product parts. The second group of clustering variables is represented by the parameters obtained *via* LC modeling on data collected from the assembly process. Several LC models are considered for that purpose, but only the parameters describing the learning rate are incorporated in the clustering procedure.

In the second step, the groups of variables from Step 1 are evaluated in terms of their efficiency in terms of clustering. We aim at defining which clustering variables are to be used, and the best number of clusters to be considered. For that matter, a "leave one variable out at a time" procedure is used, and the performance of the clustering procedure is evaluated by means of SI. This iterative process is replicated for a range of reasonable number of clusters. We now describe these two operational steps in detail.

14.2.1 Step 1

In Step 1 we define the two groups of clustering variables, which will enable an optimized grouping of product models. We initially select the products to be analyzed. Products with a large number of models (or variations) are preferred, since they potentially allow an *ad-hoc* clustering of models, which leads to an optimized data collection. In addition, market considerations play an important role in product selection: products chosen must be relevant to the company and must present a clear demand for customization.

The first group of clustering variables is obtained through expert analysis and is referred to as specialists' variables (SV). Product models are described in terms of their relevant characteristics, including physical aspects, number of parts, and complexity of its manufacturing operations. Such characteristics may be objectively or subjectively assessed, and either continuous or discrete scales can be used to describe product characteristics.

The second group of clustering variables comes from LC modeling and is referred to as model variables (MV). To obtain those MV readings we must select teams of workers, from which performance data will be collected. Teams must be comprised of workers familiar with the operations to be analyzed. We recommend collecting data from teams with low turnover in that the estimated LC parameters would be able to characterize teams across the time.

LC data is collected from teams performing bottleneck manufacturing operations in each product model. Bottleneck operations are seen as complex manual operations that demand more from workers in terms of learning time and dexterity.

The assignment of product model to teams may be performed as in Anzanello and Fogliatto (2007), or following the company's production plan. Performance data must be collected from the beginning of the operation and should last until no major modifications are noted on the data being collected. This data collection is performed by counting the number of units processed in each time interval.

Performance data collected from the process are analyzed using the LC models in (14.1)–(14.4). These models were chosen based on their performance when modeling learning data (see Nembhard and Uzumeri 2000, Anzanello and Fogliatto 2007). We use the outputs provided by the four LC models to ensure that variations on workers' learning rates are captured.

Estimates of the learning rate parameters may be obtained through nonlinear regression routines available in most statistical packages. The learning rate provided by each LC model will lead to a clustering variable, in Step 2. Note that we use only the learning rate parameter from the LC models. This is justified since production runs in customized environments are too short and do not enable final performance to be evaluated.

14.2.2 Step 2

In Step 2 the objectives are (1) to select the best clustering variables leading to an optimized product grouping procedure, and (2) to identify the ideal value for k (the number of clusters). Clustering variables from both groups (*i.e.*, SV and MV) should be evaluated since a combination of such variables may lead to the best clustering results. In addition, we recommend scaling both SV and MV variables before conducting the clustering process, since the variables may differ in units and magnitude.

We initially define a suitable interval of clusters $[k_{\text{lb}}, K]$ to be evaluated in the iterative process, where k_{lb} is the lower bound on the number of clusters and K is the upper bound. We recommend a lower bound of two clusters ($k_{\text{lb}} = 2$), while K is defined by the analyst. A k-means nonhierarchical clustering procedure using the specified k is run using all clustering variables (SV + MV), and SI is evaluated for that initial scenario. The value of SI obtained for that case is just a reference value, and may be used to assess the performance of the proposed clustering variable selection method.

Next, one variable at a time is left out of the clustering procedure, and an average SI value is computed for each instance. Note that a SI_j value is calculated for each observation j (product model) assigned to a family, and then an average SI is estimated. Once all clustering variables have been tested (*i.e.*, omitted once), the variable responsible for the maximum average SI is eliminated as the one that contributes the least in separating the products in families. The iterative procedure is then repeated for the $\text{SV} + \text{MV} - 1$ remaining variables, and the average SI is again evaluated after each variable is omitted. We repeat this procedure until a lower bound of remaining variables is reached. A graph relating the average SI and the number of retained variables may be generated to identify the ideal number of variables to be used in clustering applications. A hypothetical example of the average SI profile generated by variable elimination is illustrated in Figure 14.1 for $k = 3$. Note that the average SI increases when fewer variables are retained. In this case, the maximum average SI is obtained when 2 out of 10 variables are retained.

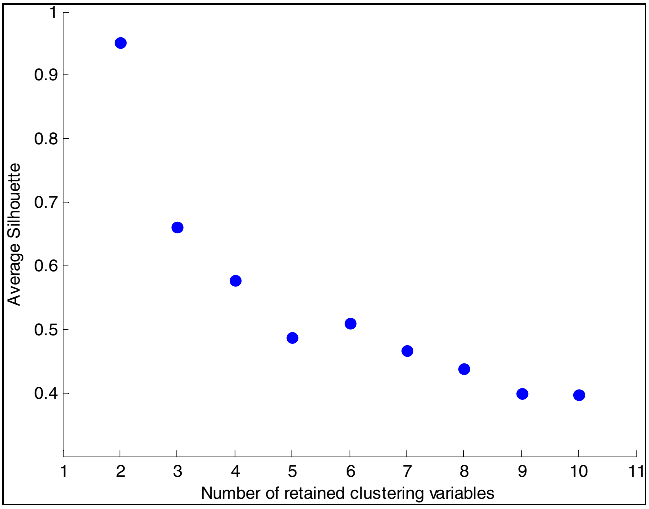

Figure 14.1 Hypothetical average SI profile with clustering variable elimination

In order to define the best number of clusters to be used, we then set $k = k + 1$, and restart the iterative elimination procedure with the SV + MV clustering variables. The variable elimination is repeated as described above and the maximum average SI is stored for that k. The iterative process stops when $k = K$.

The maximum SI value for each k, as well as the variables leading to that value, may be represented in a table. The overall maximum SI indicates the best number of clusters k as well as the clustering variables to be used.

14.3 Numerical Case

The proposed method was applied in a shoe manufacturing plant. Shoe producers have been challenged by decreasing lot sizes in the past decade, forcing their mass production configuration to adapt to an increasingly customized market. In terms of production planning, it is mandatory to cluster such large variety of models to make resource allocation more efficient. The proposed method for selecting the best clustering variables was tested in the sewing stage of the shoe manufacturing company. The sewing is the bottleneck production stage, from which data for the LC modeling were collected.

20 shoe models were considered in the study. SV were defined with respect to manufacturing complexity of the upper part of the shoes: parts complexity (deployed into four categories), number of parts in the model, and type of shoe. The first five variables were subjectively assessed by company experts (assembly line supervisors and operators, and sales department personnel) using a three-point scale, where 3 denotes the highest complexity or number of parts. The variable type of shoe has two levels: one for shoes and sandals, and two for boots, which tend to be more complex in terms of assembly. Table 14.1 displays the 6 SV and the respective ID.

Performance data were collected from three teams of workers. Shoe models were directed to teams according to the company's production planning. Performance data collected were registered as number of pairs produced in 10 min intervals, and were adjusted to the models in (14.1)–(14.4). The resulting learning parameters from the LC modeling were scaled in the interval 0–3 to ensure consistency with the SV and referred to as model variables (MV), as presented in Table 14.2.

The proposed method was run for *k* in the interval [2, 7]. Table 14.3 displays the average SI profile with the clustering variable elimination for each *k*. The bold value indicates the maximum average SI for each case, while the ID of the selected variables is presented at the bottom of the same table. A reduced number of variables is preferred in all cases, as implied by the increasing SI profile. That

Table 14.1 Specialists' clustering variables (variable ID presented in parenthesis)

Shoe ID	Specialists' clustering variables (ID in parenthesis)					
	Sewing complexity (1)	Adornments complexity (2)	Lining complexity (3)	Material complexity (4)	Number of parts (5)	Type of shoes (6)
Shoe1	1	1	1	1	2	2
Shoe2	1	1	2	2	1	1
Shoe3	1	1	2	1	2	1
Shoe4	2	1	1	1	2	1
Shoe5	1	2	2	1	2	1
Shoe6	1	1	1	1	1	1
Shoe7	1	1	1	2	1	1
Shoe8	2	3	1	1	1	1
Shoe9	2	2	1	2	2	1
Shoe10	2	2	1	2	1	1
Shoe11	1	3	1	1	2	1
Shoe12	2	2	1	2	2	1
Shoe13	1	2	1	2	2	1
Shoe14	1	2	1	2	2	1
Shoe15	2	3	2	3	2	1
Shoe16	1	3	2	3	2	1
Shoe17	2	2	2	2	3	1
Shoe18	2	3	2	3	2	1
Shoe19	2	3	2	2	2	2
Shoe20	2	3	2	2	3	1

Table 14.2 Model clustering variables (variable ID presented in parenthesis)

Shoe ID	Model clustering variables (ID in parenthesis)			
	Hyperbolic (7)	Exponential (8)	Wright (9)	Knecht (10)
Shoe1	2.00	3.00	0.73	2.48
Shoe2	1.97	1.54	1.26	2.61
Shoe3	2.27	3.00	0.86	2.53
Shoe4	2.12	2.00	1.01	2.58
Shoe5	0.60	0.94	0.51	2.46
Shoe6	0.14	0.24	1.82	2.72
Shoe7	1.67	1.52	1.07	2.60
Shoe8	0.97	0.65	1.02	2.56
Shoe9	0.58	0.44	1.53	2.70
Shoe10	0.36	0.54	1.17	2.64
Shoe11	0.81	1.44	2.41	2.90
Shoe12	1.09	0.89	2.69	2.92
Shoe13	0.42	0.57	3.00	3.00
Shoe14	0.61	0.65	2.59	2.89
Shoe15	0.93	1.92	0.80	2.52
Shoe16	0.88	1.30	1.29	2.65
Shoe17	0.50	0.59	1.80	2.74
Shoe18	3.00	1.69	2.97	2.94
Shoe19	0.26	0.49	0.63	2.49
Shoe20	0.71	1.12	1.56	2.69

indicates that the use of all clustering variables incorporates noise to the clustering procedure and decreases the grouping performance. In addition, we note that the best reduced sets for all values of k evaluated are composed of a combination of variables belonging to SV and MV. That demonstrates that both the specialists' assessment, represented by SV, as well as the workers' learning process, represented by MV, play an important role in the clustering procedure.

According to Table 14.3, $k=2$ is the best number of clusters to be considered when using a k-means procedure, and variables 6 and 10 (type of shoe and Knecht's learning rate parameter, respectively) should be used. An analysis based in four clusters (*i.e.*, $k=4$) may also lead to satisfactory results when variables 3 and 10 (lining complexity and Knecht's learning rate parameter, respectively) are considered.

It is important to mention that a random value of the order 10^{-4} was added to the SV variables due to the reduced number of points on the scale describing those variables. This enables the k-means algorithm to define clusters even when a reduced number of variables are considered, especially during the elimination steps for upper values of k. That modification does not significantly affect the precision of the clustering procedure, according to our experiments. The addition of a random value may be avoided if products are described by scales consisting of larger number of points (*e.g.*, a 1ten-point scale) or if a continuous scale is adopted.

Figure 14.2 brings the silhouette graph for $k=2$ when only the SVs are considered. This leads to an average SI of 0.4720. Each horizontal line represents the adherence of observation j (*i.e.*, a shoe model) to the cluster it was assigned to. In

Table 14.3 Average SI and selected clustering variables

Number of retained clustering variables	Number of clusters (k)					
	2	3	4	5	6	7
2	0,95	0,71	0,83	0,68	0,71	0,53
3	0,80	0,63	0,74	0,71	0,71	0,60
4	0,73	0,59	0,63	0,63	0,73	0,62
5	0,67	0,55	0,57	0,50	0,64	0,58
6	0,62	0,46	0,51	0,44	0,53	0,51
7	0,60	0,44	0,52	0,45	0,45	0,51
8	0,56	0,42	0,44	0,42	0,44	0,45
9	0,47	0,42	0,40	0,40	0,44	0,42
10	0,43	0,37	0,37	0,37	0,37	0,41
Retained clustering variable ID	6 10	2 8	3 10	4 8 10	3 7 9 10	2 7 9 10

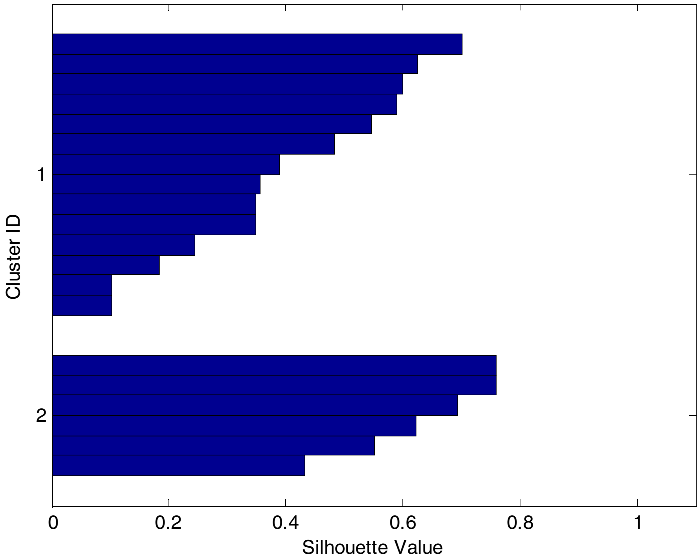

Figure 14.2 Silhouette graph using only SV

Figure 14.2, 14 shoes were assigned to cluster 1 and 6 to cluster 2. Some observations included in cluster 1 assume very low SI values, denoting an improper cluster assignment.

Figure 14.3 illustrates the silhouette graph when using the selected variables and *k* = *2*. There is a remarkable improvement in the adherence of the observations to the clusters. The same graph demonstrates that most product models actually belong to cluster 2, and not to cluster 1 as previously indicated by the SV alone. The average SI for this case is 0.9588.

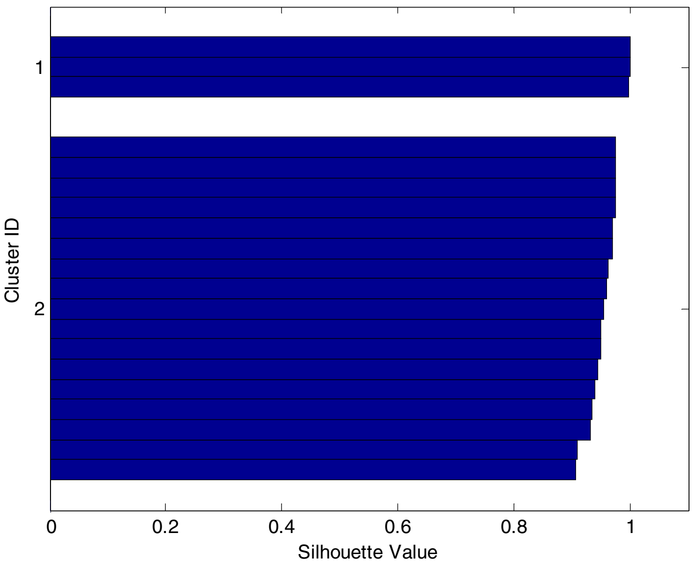

Figure 14.3 Silhouette graph using the selected variables

It is important to emphasize that small variations on the average SI may occur due to two factors: (1) the random value added to the SV variables, although small, may result in slightly different allocations of observations to clusters, and (2) the *k*-means algorithm used in this case study randomly defines its clusters centroids (also referred as "seeds"). This may lead to different allocations of observations to clusters even when using the same data and consequently affect the average SI.

14.4 Conclusion

Clustering is an important technique in highly customized production environments, where a large variety of product models and reduced lot sizes are typical. It allows product models with similar characteristics and processing needs to be aggregated into families, increasing the efficiency of production programming and resources allocation. The quality of the clustering results, however, relies on using a limited set of relevant clustering variables.

This chapter presented an iterative procedure aimed at selecting the most relevant clustering variables in processes where workers' learning takes place. Workers' learning rates were addressed by means of LC modeling, and the estimated LC parameters were incorporated in the grouping procedure as clustering variables. The best variables were identified by combining a "leave one variable out at a time" procedure with a k-means clustering technique. The less relevant variables were identified by means of the SI, which also defined the ideal number of clusters.

When applied to a shoe manufacturing case study, the method led to significant reduction of clustering variables needed for grouping, while increasing the clustering quality compared to using only the variables describing product's characteristics. We also demonstrated that a combination of variables assessed by production experts and variables generated by the LC modeling leads to the best set of clustering variables for a considerably wide range of numbers of clusters.

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Chapter 15
Re-examining Postponement Benefits: An Integrated Production-inventory and Marketing Perspective

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Abstract This chapter presents a new perspective to obtain a better understanding of postponement benefits. This new perspective tries to address the important alignment between the production-inventory and marketing functions, under which we are able to obtain a more complete view on how postponement may enhance firms' profitability. We developed stylised models to capture the interactions between several factors including inventory, lead time, price and product

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variety. Through numerical examples we show how postponement facilitates the attainment of a higher profit as the result of improved capability in compromising product variety and delivery lead time, on top of cost savings associated with reduced inventories.

Abbreviations

DD	Delayed differentiation
HP	Hewlett-Packard
i.i.d.	Independent and identically distributed
MTO	Make-to-order
MTS	Make-to-stock
PC	Personal computer

15.1 Introduction

Postponement or delayed product differentiation is an important concept used to accommodate mass customization, particularly in dealing with uncertainty due to proliferation in product varieties and uncertain demands from customers. This is achieved by properly designing the product structure and the manufacturing and supply chain process so that one can delay or postpone the final customisation of the product as much as possible, pending more accurate product demand information. Postponement offers a compromised solution between the two extreme make-to-stock and make-to-order policies. The unfavourable consequence of a make-to-stock policy characterised by a high level of inventory or lost sales due to forecasting errors is minimised through the customisation of the intermediate goods based on observed demand. At the same time, the long lead time associated to a make-to-order policy is reduced by making intermediate goods to stock.

The concept has received considerable attention from researchers and practitioners in recent years and is perceived as one of the major supply chain management practices having discernible impact on competitive advantage and organisational performance (Li *et al.* 2006). One of the classic examples of successful postponement application is Hewlett-Packard's (HP) for their DeskJet printers (Lee *et al.* 1993, Feitzinger and Lee 1997). The company opted to customise the printers at its local distribution centres rather than at its factories. For example, instead of customising the DeskJet at its factory in Singapore before shipping them to Europe, HP has its European distribution centre near Stuttgart, Germany to perform this job. HP restructured its printer production process by manufacturing a generic Deskjet printer and later localising the generic product by plugging in the localised modules (power supplies, packaging and manuals) at its local distribution centres. This way, HP was able to maintain the same service levels with an 18% reduction in inventory, saving millions of dollars. Another celebrated example is Benetton who used postponement to cope with volatile fashion trends and long production lead-times (Sigronelli and Hesket 1984, Dapiran 1992). By using un-dyed yarn to knit about half of its clothing and delaying the dying process to a later stage, Benetton has a better idea of the popular colours for the season. Other examples include IBM (Swaminathan and Tayur 1998), Whirpool (Waller *et al.* 2000) and Xilinx (Brown *et al.* 2000).

Although there is a long list of publications showcasing postponement as an attractive means to accommodate mass customisation, our literature review suggests that most of the extant academic literature focuses on the evaluation of postponement in the context of production-inventory systems and is strongly based on a cost-minimisation strategy (*e.g.*, Lee and Tang 1997, Garg and Tang 1997, Aviv and Federgruen 2001a, b, Gupta and Benjaafar 2004). The most prevalent finding says that postponement is beneficial due to a significant reduction of the total inventory cost achieved by reducing demand forecast errors and delaying expensive operations, which enable companies to maintain the bulk of its inventories in the cheaper and/or pre-customised form (Lee *et al.* 1993, Swaminathan and Lee 2003). A very common setting used in that type of evaluation is that demand from customers is assumed to be constant, *i.e.*, the impact of factors such as price, lead time and product characteristic on customers' purchase decision is ignored.

With the recent emphasis on integrative, customer-focused decision making, it can be argued that there is a need to explore some cross-functional implications and coordination issues of any particular supply chain strategies. This argument is also in line with one of the authors' experience in studying the implications of various supply chain redesign strategies adopted by a major European manufacturer of personal computers (Berry and Naim 1996). The study, in particular, presents a series of ongoing supply chain redesign strategies in the company including just-in-time, interplant logistics and planning integration, vendor integration, and strategic positioning of decoupling point or postponement. The study reported significant operational improvements achieved from the implementation of such strategies as measured by significant reductions in the total inventory, lead time and order amplification or bullwhip effect. Despite all these benefits, it was recognised that the study was not capable of capturing the cross-functional implications by, for example, linking operational and marketing decisions.

In the context of mass customisation in particular, there are many aspects pertinent to production-inventory and marketing functions. This is especially true when we consider the fact that the customisation is not "free" and needs to be traded-off against lead time, cost and other factors (McCutcheon *et al.* 1994, Squire *et al.* 2006). Techniques such as postponement have proven to be supportive of firms moving from mass production to mass customisation when looked at from the production-inventory perspective, *i.e.*, it is able to minimise the total inventory cost associated with uncertainties due to proliferation in product varieties. However, one may question whether postponement is also beneficial when looked at from a marketing perspective. When firms move from mass production to mass customisation by employing postponement, one might question whether, for example, there would be an effect of longer lead times on customers' willingness to buy, which will consequently influence the total profitability. Similarly, firms' decisions on product price cannot be ignored. The product price must be optimised by taking into account product varieties and inventory cost reductions achieved through postponement balanced against customers' dissatisfaction due to longer lead times.

Therefore, we argue that the currently dominating analysis focusing solely on the production-inventory system is incomplete because such an analysis pays no attention to the presence of marketing factors such as the sensitivity of customers' purchase decisions to product varieties, prices and delivery lead times. Furthermore, that type of analysis is grounded to the traditionally narrow view that overlooks the importance of coordination between different functional areas. This chapter aims to re-examine the role of postponement based on an integrated approach that takes into account both the production-inventory as well as marketing factors.

To the best of our knowledge, this chapter represents the first formal approach to evaluating postponement by considering the marketing-manufacturing interface. Consequently, this new approach would require the use of a profit-maximisation strategy instead of a cost-minimisation strategy. One of the results in this study, in fact, shows that postponement benefits assessed by the cost minimisation strategy are not equivalent to those assessed by the profit maximisation strategy. Furthermore, this new approach is also capable of capturing the interaction between factors such as the lead time, product variety trade-off and its implication on the profitability. To some degree firms can use postponement to mitigate this trade-off, but they cannot eliminate it as Squire *et al.* (2006) show empirically.

We explicitly compare two manufacturing configurations. The first configuration represents a make-to-stock (MTS) system in which multiple product variants are processed through a single-stage production. The second configuration represents a system employing postponement and is modelled as a two-stage production inventory system. Stage 1 produces intermediate goods that are common for all finished products and stage 2 differentiates finished products. Intermediate goods are made-to-stock and then differentiated only after customer demand is achieved. Queuing models are used for the analysis of production and inventory systems. Our marketing model of product differentiation is based on the Hotteling's locational model of customer choice behaviour (Hotelling 1929), which is widely used in the economic and marketing literature (*e.g.*, Lancaster 1990, Syam and Kumar 2006). The model captures the situation in which demand is not only sensitive to price and product characteristic, but also to delivery lead time. An integrated production-inventory and marketing model is then formulated for each of the two configurations and serves as the basis for assessing postponement benefits.

Our main interest in this chapter is to extend the current understanding of postponement particularly in order to better explain how postponement may enhance the total profitability. A better explanation should be able to reveal how postponement facilitates the attainment of higher revenues as a result of improved capability in compromising product variety and delivery lead time, on top of cost savings associated to reduced inventories. Furthermore, examining how postponement benefits are different when evaluated by the cost-minimisation strategy in contrast to the profit-maximisation strategy is also of interest.

The rest of the chapter is organised as follows. In the next section we provide a survey of the relevant literature. Section 15.3 outlines the notation and modelling assumptions and presents all the models. In Section 15.4 we present the numerical experiments and analyse the results and in Section 15.5 we wrap up the chapter with a concluding discussion and some suggestions for future research.

15.2 Literature Background

In this section we discuss the relevant literature with emphasis on the two streams of research that we consider most relevant to this work. The first stream of research is on postponement and the second is deals with the alignment of marketing and production-inventory functions. We summarise our review of these two streams in the following sections.

15.2.1 Postponement to Accommodate Mass Customisation

There is a large body of literature on postponement. We refer the reader to van Hoek (2001), Swaminathan and Lee (2003), Yang *et al.* (2004) and Boone *et al.* (2007), who provide a comprehensive review of research on postponement. The concept of postponement was actually introduced in the literature by Alderson (1950) as a means of reducing marketing costs. He believed that risks related to marketing operations could be reduced by postponing changes in form and identity to the latest possible point in the marketing flow or postponing change in inventory location to the latest possible point in time. Over time, a number of authors have introduced different conceptual categorisations of postponement strategies extending the understanding of where and when postponement is appropriate. In the paper by Zinn and Bowersox (1988), five different types of postponement strategies are identified. Four different strategies of form postponement (labelling, packaging, assembly and manufacturing) which, when combined with time postponement, constitute the five postponement strategies. Bowersox and Closs (1996) made a clear differentiation between logistics postponement and form or manufacturing postponement. Logistics postponement can be seen as a combination of time and place postponement (where place postponement refers to the storage of goods at central locations in the channel until customer orders are received). Pagh and Cooper (1998) provided a classification of postponement applications in the mid- to down-stream stages of the supply chain. Their classification is in fact a reworked version of the classification suggested by Zinn and Bowersox (1988). They identified four generic strategies by combining manufacturing and logistics postponement and speculation. These include: the full speculation strategy, the logistics postponement strategy, the manufacturing postponement strategy and the full postponement strategy. Rabinovich and Evers (2003) studied the effects of time and form postponement on inventory performance. Supported by an empirical survey, their study shows that the joint implementation of time and form postponement is synergistic in nature, giving a positive impact as reflected in a lower proportion of speculative inventory.

Analytical models measuring the costs and benefits of postponement are presented by Feitzinger and Lee (1997), Lee and Tang (1997) and Garg and Tang (1997). They show that the key benefit of postponement is from reductions in safety stock levels due to risk-pooling while the cost of designing the generic component is the main drawback. Aviv and Federgruen (2001a, b) studied postponement by considering a two-stage system in which stage 1 produces undifferentiated items that are later differentiated in stage 2. They introduced the possibility of learning from past realisations of demand as an additional factor that contributes to the value of postponement. They derived the resulting savings in safety stock and show that learning increases the value of postponement. In all these models, the effect of queuing at the production facility is ignored so that lead times are exogenous to the model and assumed to be constant. One of the main limitations of these models is that the existence of the interaction between the production facility utilisation and processing time variability in affecting order delays has been ignored.

Models that endogenise lead times are presented by Gupta and Benjaafar (2004) and Su *et al.* (2005). As in this chapter, those models explicitly take into account the queuing effect as a result of considering a capacitated production facility. Gupta and Benjaafar (2004) considered the capacitated production system employing form postponement as a two-stage system where a common product platform is produced in an MTS fashion in the first stage, which is then differentiated into different products in the second stage in a make-to-order (MTO) fashion. Su *et al.* (2005) compared two specific configurations. In the first configuration products are produced after orders arrive (MTO mode). The second configuration represents the system employing form postponement. Different from Gupta and Benjaafar, Su *et al.* (2005) examined the system where the second stage produces differentiated products in an MTS fashion instead of an MTO fashion. More recently, Wong *et al.* (2009) examined different postponement configurations characterised based on the positioning of the differentiation point and the customer order decoupling point.

There is a wealth of literature analysing postponement, though, to the best of our knowledge, the approach considering an integrated production-inventory and marketing framework has never been developed.

15.2.2 Production-inventory and Marketing Coordination

There exist several papers that study the coordination of marketing and operations decisions similarly to us. De Groote (1994) analysed the joint problem of marketing/manufacturing coordination with the focus on the exploration of some cross-functional implications of the flexibility of manufacturing processes. He formulated two complementary problems: the marketing choice of the breadth of the product line and the manufacturing choice of the flexibility of the production process. One of the key results is that the decentralised solution of the two problems typically yields a suboptimal solution. Dobson and Yano (2002) examined a product line design problem in which a manufacturer faces demand that is influenced by both price and lead time. The firm must decide which products to offer, how to price them, whether each should be made to stock or made to order, and how often to produce them. The offered products are assumed to share a single manufacturing facility where setup times introduce diseconomies of scope and setup costs introduce economies of scale. They assume deterministic demand thatI linearly decreases in price and lead time. Different from De Groote (1994) and this work, the models presented by Dobson and Yano (2002) do not take into account how the number of product variants influences customers' purchase decision. In comparison to the above mentioned two papers, the focus of our analysis is different in that we are particularly interested in comparing different manufacturing configurations in the context of mass customisation.

Jiang *et al.* (2006) compared two configurations; namely mass customisation and mass production. In their model, the mass customistion system consists of two stages: the initial build-to-stock phase and the final customise-to-order phase. The mass production system has a single stage that builds products with pre-determined specifications to stock. Our analysis is different from theirs mainly in the following respects. Firstly, their model ignores the effect of congestion at the production facility while we explicitly model the queuing effect as a result of considering a capacitated production facility. Secondly, they do not include delivery lead time as a factor that affects customers' purchase decision as we do. Finally, Alptekinoglu and Corbett (2007) analysed the trade-off between the increased ability to precisely meet customer preferences and the increased lead time from order placement to delivery associated with customised products. The analysis presented in this chapter is different as our main focus is to evaluate the relative merits of postponement compared to the make-to-stock policy while their interest is to determine an optimal product line design in which it is possible to have a combination of made-to-stock and made-to-order products.

15.3 The Models

15.3.1 Description of Manufacturing Configurations

We distinguish two manufacturing configurations. In the first configuration, postponement is not employed and a set of finished products is produced in an MTS mode. Items are produced ahead of demand and kept in stock, ready to be shipped upon receipt of orders. This configuration is modelled as a one-stage production-inventory system. The second configuration employing postponement is modelled as a two stage production-inventory system, where stage 1 produces a component that is common for all finished products and stage 2 differentiates finished products. This configuration maintains stocks of a generic component and differentiates the finished products only after demand is realised. Throughout this chapter we term these two configurations MTS and delayed differentiation (DD). Figure 15.1 illustrates the two configurations.

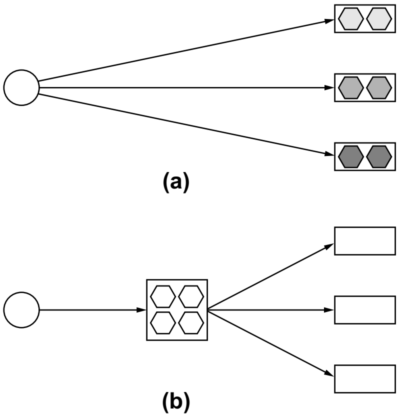

Figure 15.1 One-stage MTS (a) and two-stage DD configurations (b)

15.3.1.1 Configuration I: Make-to-stock System – No Postponement

Consider a manufacturer who offers N finished product variants, indexed by $i = 1$, 2, …, N. We denote d_0 as the aggregate demand rate, where $d_0 = \sum_{i=1}^{N} d_i$. We model this configuration as a single stage production-inventory system. End customer demand of product i arrives in single units according to a Poisson process with rate d_i. Note that, as explained in the previous section, the demand level is a function of price and lead time. We assume that the manufacturing processing times are independent and identically distributed (i.i.d.) random variables and exponentially distributed with a mean processing rate of m (the average manufacturing lead time is equal to $1/m$). These assumptions make the analysis tractable without a significant loss in accuracy, especially as our emphasis is in deriving qualitative patterns and managerial insights. For stability, we require that $d_0 / m = \rho < 1$. For the MTS configuration, demand is satisfied from stock unless the corresponding inventory is empty. All shortages are backlogged. We assume that a base-stock policy is used for the inventory control. Under this assumption, each demand triggers the immediate release of raw material, which is assumed to always be available (see Buzacott and Shathikumar (1993) for a formal definition of a base stock policy). Let S_i denote the base stock level for finished product i. Furthermore, changeover times between products are assumed to be negligible.

15.3.1.2 Configuration II: Mass Customisation with Delayed Differentiation

We model this configuration as a two-stage production-inventory system where stage 1 produces a component that is common for all finished products and stage 2 differentiates finished products. This configuration can be seen as a hybrid strategy in which a generic component is built-to-stock and then differentiated only after customer demand is realised. We assume that the processing times for stages 1 and 2 are i.i.d. random variables and exponentially distributed with mean processing rates of m_1 and m_2, respectively, and that $1/m_1 + 1/m_2 = 1/m$. We define $f(0 < f < 1)$ as the fraction of the mean total processing time consumed by the generic component. Thus, we may write $m_1 = m/f$ and $m_2 = m/(f-1)$. Small f values represent early postponement while large f values represent late postponement. Again, we require that $d_0/m_j = \rho_j < 1$ for $j = 1$ and 2, where ρ_j is the j-stage utilisation rate. The base stock level for generic components is denoted as S_0, while the stock level for finished products is zero for all $i = 1, 2, \ldots, N$. Here we also assume negligible changeover times.

Let c_{MTS} and c_{DD} denote the unit production cost for each of the manufacturing configurations, respectively. We assume that these two costs are identical, so that at the very least this gives us an upper bound on the benefits of postponement. Let h denote the holding cost *per* unit *per* unit time for all finished products, and h_0 denote the holding cost *per* unit *per* unit time for the generic component. For both configurations there is a product proliferation cost *k*, incurred every time the manufacturer offers a new product variant. This cost could include redesign, *tooling* and setup costs. The linearity assumption of product proliferation cost in the number of products is in line with common observations in the operations literature (Thonemann and Bradley 2002, Benjaafar *et al.* 2004). All the notations used throughout the paper are presented in Table 15.1.

Table 15.1 List of notations

Demand input parameters	
d_0	Total potential demand rate
π_i	First choice probability of product *i*
Θ	Customers' ideal taste
d_i	Demand rate for product *i*
R	Customer reservation price
$1-\beta$	Service level
Production input parameters	
m	The production rate for the MTS configuration
m_1	The production rate at stage 1 for the DD configuration
m	The production rate at stage 2 for the DD configuration
f	The fraction of the total lead time required to make the generic component

Table 15.1 Continued

Cost parameters	
h	Unit inventory holding cost for the finished product
h_0	Unit inventory holding cost for the generic component
c_{MTS}	Unit production cost for the MTS configuration
c_{DD}	Unit production cost for the DD configuration
k	Product proliferation cost
c_x	Linear transportation cost
c_t	Linear delay or waiting cost
Decision variables	
S_i	Base stock level for the finished products
S_0	Base stock level for the generic component
$\mathbf{S}$	Vector of base stock levels
N	Number of product lines
x_i	Product i 's characteristic
$\mathbf{x}$	Vector of product characteristics
p	Product price
T	Promised delivery lead time
Performance measures	
I_i	Expected on-hand inventory for the finished products
I_0	Expected on-hand inventory for the generic component
Z	Expected total profit

15.3.2 The Marketing Model

Our marketing model is based on a location model of customer choice behaviour, which is well known in the economics and marketing literature. It is along the lines of the spatial location model of Hotelling (1929) and its extensions (Lancaster 1990). We consider a monopolistic situation where the manufacturing firm serves a market with heterogeneous customers over a single time period. Customers' preferences are uniformly distributed over a closed interval of the product space [0, 1]. The product offerings are horizontally differentiated, each characterised by a single point in that interval quantified by a real number between 0 and 1. We are aware that mass customisation may also include a range of product offerings with vertical differentiation, in which case products offered are different with respect to their qualities. For MP3 players, the horizontal differentiation would be due to different colours or other "taste" attributes, while the vertical quality differentiation would be due to different memory size. However, in order to simplify the analysis we focus on the horizontal product differentiation and leave the inclusion of vertical differentiation as a future research opportunity.

Products are offered with price p, assumed to be identical for all products. The uniform pricing scheme is reasonable when the products are horizontally differentiated with qualities of products at the same level. Each customer buys one unit from the manufacturer and has her own ideal product represented by her location $\theta \in [0, 1]$. Our marketing model captures the situation in which demand is not only sensitive to price and product characteristics, but also to delivery lead time. We assume that the manufacturer commits to satisfying promised lead time t for all products and maintaining a service level of $1\text{-}\beta$ (*i.e.*, delivery occurs within t time units with $1\text{-}\beta$ probability). The disutility of customers incurred when buying their non-ideal product is represented by a linear transportation cost c_x *per* unit distance between their ideal product and the purchased product. Further, there is also a linear delay cost c_t *per* time unit of delivery or waiting time. Higher values of c_x and c_t mean customers are more sensitive to the deviation from their ideal products and the waiting time, respectively.

The utility of customer whose ideal taste is θ from buying product i with characteristic x_i, price p and delivery time guarantee t is given by

$$U(\theta, x_i, p, t) = r - p - c_t t - c_x \mid \theta - x_i \mid, \tag{15.1}$$

where r is a reservation price, defined as the maximum amount of money customers are willing to spend to buy the products. All customers are assumed to have a common reservation price. A customer buys the product that maximises her utility provided that it is non-negative, otherwise she does not make a purchase. Product i is said to be the first choice of a particular customer if it gives a non-negative utility and its utility is the maximum among all products offered by the manufacturer. Denoting π_i as the *first choice probability* of product i, the demand rate for product i can be defined as $d_i = \pi_i d_0$, $i = 1, 2, \ldots, N$. We assume that r is large enough so that the net utility is always greater than zero and so all customers will buy a product. Consistent with this, we also assume that complete market coverage is optimal. This assumption is common in the marketing and economics literature (Alptekinoglu and Corbett 2007).

To determine an optimal design of the product line, we use the well known optimality condition for Hotteling's location model, which ia also identified in de Groote (1994) and Gaur and Honhon (2006). That is, for a given N, the optimal product line has a simple structure: the market should be partitioned in segments of equal lengths, the characteristics of the products should correspond to the taste of the customers located in the middle of the segments and the manufacturer should set prices to make customers located at the extreme of the segments indifferent between buying and not buying.

Consider the example shown in Figure 15.2. In this particular example, the manufacturer offers one product ($N = 1$). The guaranteed delivery time t is assumed to be known (as the consequence of the inventory decision). Following the optimality condition stated above, the optimal product design is obtained by setting the product's characteristic at $x^* = 0.5$. As there is only one segment for $N = 1$, that characteristic corresponds to the taste of the customers located in the middle of the segment. Furthermore, Figure 15.2 also shows two disutility functions that correspond to two different prices. The price p_B leads to full market coverage, *i.e.*, $\pi_B = 1$ while a higher price, p_A, leads to a lower market coverage ($\pi_A < \pi_B$). In this case, p_B is the maximum price that gives full market coverage and makes the customers located at the extreme of the segment indifferent to buying or not buying, as indicated by the disutility value being equal to the reservation price. As we assume that full market coverage is optimal, given that *N* and *t* are fixed, it is straightforward to see that p_B is the optimal price. All prices less than p_B are suboptimal because they result in lower revenues.

Consider now the other example shown in Figure 15.3, in which the manufacturer offers two products (*N*=2). Given that there are two segments, the optimal design of the product line is obtained by setting the two products' characteristics at $x_1^* = 0.25$ and $x_2^* = 0.75$, and price at *p*. The two characteristics partition the market into two segments of equal lengths and correspond to the taste of the customers located in the middle of the two segments. Moving away from these characteristics, as illustrated by setting the second product characteristic at x_1 instead of x_1^*, will lead to a suboptimal situation as a result of lower total market coverage.

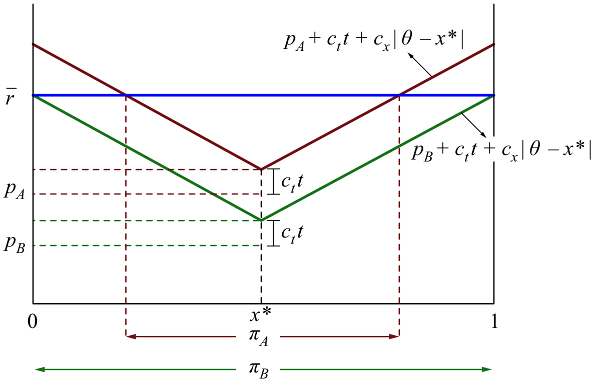

Figure 15.2 An example of the disutility function for one product

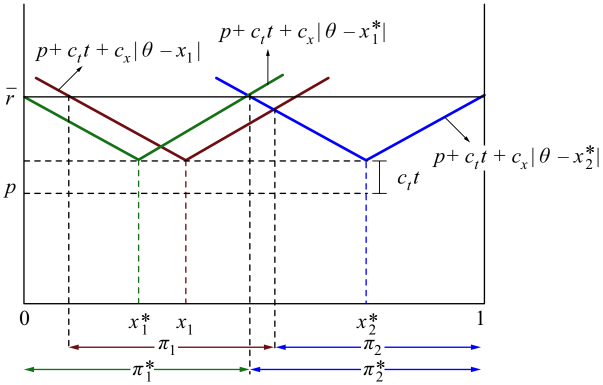

Figure 15.3 An example of the disutility function for two products

To put it more formally, given that N, t, c_t and c_x are fixed, we obtain full market coverage with the maximum revenue by setting:

$$x_1^* = \frac{2i-1}{2N}, i = 1, 2, ..., N \tag{15.2}$$

$$p^* = r - c_t t - \frac{c_x}{2N}. \tag{15.3}$$

From (15.2) and our assumption of the optimality of complete market coverage, it is easy to show that $\pi_i = 1/N$ and $d_i = d_0/N$ for all $i = 1, 2, \ldots, N$.

15.3.3 The Production-inventory Model

In this section we present the models used to evaluate the production-inventory systems for each of the two configurations.

15.3.3.1 The MTS Configuration

Following Buzacott and Shanthikumar (1993), for a given base stock level, the expected inventory for finished product i is given by

$$I_i(S_i) = S_i - \left(\frac{d_i}{m-d_0}\right)\left(1-\hat{\rho}_i^{S_i}\right), \tag{15.4}$$

where $\hat{\rho}_i = d_i/(m-d_{-i})$ and $d_{-i} = \sum_{j \neq i} d_j$. The probability that the order-fulfilment time will not exceed a quoted lead time t ($t \geq 0$) is given by

$$P_R\left[T_i(S_i) \leq t\right] = 1 - \hat{\rho}_i^{S_i} \times e^{-(m-d_0)t} \tag{15.5}$$

The manufacturer sets a service level $1-\beta$, where $0 < \beta < 1$, guaranteeing that the actual lead time will not exceed the promised lead time, *i.e.*, $P_R\left[T_i(S_i) \leq t\right] \geq 1 - \beta$. It is very straightforward to find that for a given base stock level S_i the manufacturer will be reasonably interested in setting the promised lead time such that the service constraint is binding. We can state

$$t = \max\left(0, \frac{1}{m-d_0}\left(S^i \ln \hat{\rho}_i - \ln \beta\right)\right). \tag{15.6}$$

15.3.3.2 The DD Configuration

We use the evaluation models derived in Gupta and Benjaafar (2004). Suppose f, the proportion of the total lead time used to manufacture the generic component, is known. For a given base stock level of generic component, the expected inventory level is given by

$$I_0(S_0, f) = S_0 - \left(\frac{\rho_1 (1 - \rho_1^{S_0})}{1 - \rho_1} \right), \tag{15.7}$$

where $\rho_1 = f d_0 / m_1$. The probability that the order-fulfilment time exceeds a quoted lead time t ($t \geq 0$) is given by

$$P_r(T(S_0) \geq t) \approx \begin{cases} (1 + \rho^{S_0}(1-\rho)\mu t)e^{-\mu(1-\rho)t} & \text{if } \rho_1 = \rho_2 = \rho_3 \\ e^{-\mu_2(1-\rho_2)t} + \left(\dfrac{(1-\rho_2)\rho_1^{S_0+1}}{\rho_2 - \rho_1} \right) & \\ e^{-\mu_2(1-\rho_2)t} - e^{-\mu_1(1-\rho_1)t} & \text{otherwise.} \end{cases} \tag{15.8}$$

15.3.4 The Integrated Model

In this section we present the integrated model for each of the configurations. First, a formal expression of the optimisation problem is introduced. After that we present the solution procedure for determining the optimal solution for each configuration.

15.3.4.1 The MTS Configuration

Define $\mathbf{x} = [x_1 \; x_2 \; ... \; x_N]$ as a vector of product characteristics and $\mathbf{S} = [S_1 \; S_2 \; ... \; S_N]$ as a vector of base stock levels. We formalise the manufacturer's optimisation problem as follows.
Problem P^{MTS}

$$\text{Max } Z(N, \mathbf{x}, \mathbf{S}, p) = \sum_{i=1}^{N} (p - c_{\text{MTS}}) \cdot d_i(x_i, S_i, p) - \; h \cdot I_i(S_i) - k \cdot N \tag{15.9}$$

Recall that the optimal product line has a structure in which the market should be partitioned in segments of equal lengths. This means that for a given N, $\pi_1 = \pi_2 = ... = \pi_N$ and so $d_1 = d_2 = ... = d_N$. Because of this symmetry it is reasonable to have identical optimal base stock levels for all products, *i.e.*, $S_1^* = S_2^* = ... = S_N^*$. As already discussed in Section 15.3.2, for a given N we are able to determine the optimal $\mathbf{x}$ using (15.2) and this optimal $\mathbf{x}$ will not be affected by decisions made for the base stock level $\mathbf{S}$ and price p. We also know that when the base stock level is given, we are able to calculate the promised lead time, which in turn allows us to determine the optimal price using (15.3). This leads us to develop a two-stage based solution procedure. In the first stage, we fix N and optimise $\mathbf{S}$, and in the second stage we optimise N.

From (15.6) it can be seen that the promised lead time t linearly decreases with S before reaching a zero level. It can also be proven that $I_i(S_i)$ increases and is a convex function of S_i. This means that the expected total profit Z is a concave function of S, which helps us to determine the optimal base stock level. We are now able to determine the optimal solution for a given N. The next step is to optimise N, which can be done by gradually increasing N starting from $N = 1$. For each value of N we optimise $\mathbf{x}$, p, and $\mathbf{S}$. The search can be terminated when the following condition is met $(r - c_{MTS})d_0 \leq kN$. The left term in this condition is a constant and represents the maximum profit that can be gained by setting the price equal to the reservation price. The right term represents the proliferation cost,which linearly increases with N. So the condition ensures that no better improvement is possible by increasing N.

15.3.4.2 The DD Configuration

Problem P^{DD}

$$Z[f, N, \mathbf{x}, S_0, p] = \sum_{i=1}^{N} (p - c_{\mathrm{DD}}) \cdot d_i[x_i, S_0, p] - h_0(f) \cdot I_0[S_0, f] - k \cdot N \tag{15.10}$$

The optimal solution for the above defined problem can be obtained using a technique similar to that used in solving the problem for MTS. For a given N we need to optimise $\mathbf{S}$ and f, and then we need to optimise N. Different from the problem $\mathrm{P}^{\mathrm{MTS}}$, however, it is not easy to prove whether or not the profit function is concave in S_0. Given that f is fixed, we know that $I_0(S_0)$ is increasing in S_0 and that when S_0 is relatively large we will reach a situation where $t(S_0) \approx t(S_0 + 1)$. If we reach such a situation, no improvements can be made by increasing S_0 further. To optimise f, we use a simple search technique, which is also used in Wong *et al.* (2009). Then the next step is to optimise N, which can be done using the same technique as for solving the problem $\mathrm{P}^{\mathrm{MTS}}$.

15.4 Analyses

In this section we present the numerical analysis that focuses on two lines of enquiries as outlined in the Introduction. Firstly, we aim to get some insights from the comparison of the cost minimisation and profit maximisation strategies used for the evaluation of postponement benefits. Secondly, we are interested in assessing how postponement may actually enhance the manufacturer profitability taking into account marketing as well as production-inventory factors.

15.4.1 Cost Minimisation Versus Profit Maximisation

In this section we present numerical examples to demonstrate differences on postponement benefits when the profit maximisation strategy is used rather than the cost minimisation strategy. Consider the following system parameters:

1. aggregate demand rate $d_0 = 5$ / time unit;
2. reservation price $r = 500$;
3. production rate $m = 6$ / time unit;
4. product proliferation cost $k = 10$;
5. linear cost associated to waiting $c_t = 45$;
6. linear transportation cost $c_x = 120$;
6. unit production cost $c_{MTS} = c_{DD} = 100$;
8. unit holding cost $h_i = 20$ / time unit; and
9. service level = 98%.

Under these parameters and the integrative model, we obtain the optimal solutions for the two configurations summarised in Table 15.2.

Table 15.2 Comparison of optimal parameters (MTS *vs*. DD) – an example

Optimal parameter	MTS	DD
Expected profit	1453.50	1747.70
Price	473.16	466.89
Number of product variants	3	5
Base stock level	8	4
Promised lead time	.1520	.4691

Under the profit maximisation strategy, the benefit of postponement can be determined by calculating the relative difference of profits earned by the MTS and DD configurations (profit gain of DD over MTS). The measure we use is

$$\%PROFIT\ GAIN = \frac{Z_{DD}(f,N,x,S_0,p) - Z_{MTS}(N,x,S,p)}{Z_{MTS}(N,x,S,p)} \times 100\% \qquad (15.11)$$

For this particular example it can be shown that the profit generated by the DD configuration is 20.24% higher than the MTS configuration. It is shown in Table 15.2 that the optimal stock level for the DD configuration (four units for the generic component) is significantly less than that of the MTS configuration (eight units for each product). This inventory reduction obviously contributes to the total increased profitability. The result also shows the advantage of employing postponement in offering more product variety, thereby enhancing the customisation level. However, the example also shows the downside of postponement in terms of responsiveness. It is observed that under the same service level (98%), the promised lead time that can be offered by the DD configuration is longer than the MTS configuration. To compensate the negative effect of the longer lead time on customers' demand, the system responds by lowering the price of the products. This may sound counter-intuitive if one does not take into account the lead time *versus* product variety trade-off and ignore the fact that this trade-off has an effect on the pricing decision.

If the lead time is assumed to be the same or customers are not sensitive to delivery lead times, one would expect that customers can be charged a higher price for having more options. Likewise, while it is obvious that the greater product variety afforded by the DD configuration provides customers with some incentives to compensate the longer lead time, the optimal price of the customised products will be dependent on whether or not the incentives are sufficient. If not, then it is reasonable to set a lower price for the customised products than the standard products, as illustrated in this example. Nevertheless, it is worth noting that the result shown in this particular example should not be generalised too far by stating that, for example, the optimal price for the DD configuration (mass customisation) is always lower than the optimal price for the MTS configuration (mass production). The results will ultimately be dependent on the value of the parameters.

Now consider the evaluation of postponement based on the cost minimisation strategy. The optimisation problem based on the cost minimisation strategy can be formulated straightforwardly by removing all the marketing-related parameters from the set of decision variables. We refer the reader to Wong *et al.* (2009) for details of the model description. Under the cost minimisation strategy, the benefit of postponement is determined by calculating the relative difference in the total inventory costs

$$\%COST\ SAVING = \frac{COST_{MTS} - COST_{DD}}{COST_{MTS}} \times 100\% \tag{15.12}$$

Suppose the number of product variants for the two configurations is exogenously determined, $N=3$. For the MTS configuration the optimal stock level is $S_i=8$ for $i=1$, 2, and 3, resulting in promised lead time of $t=0.152$ with a service level of 98% and the expected inventory cost 382.33. If we apply the same service level and promised lead time to the DD configuration, the following optimal solution is obtained: the stock level of generic component $S_0=13$ and the expected inventory cost is 201.42. The postponement benefit for this particular example is as high as 47.32%.

The above calculation example clearly indicates there could be significant differences of postponement benefits when evaluated under the two different strategies. Under the cost minimisation strategy, the value of postponement can be as high as 47.32%. However, one should recognise the fact that this saving is obtained without considering the effect of product line offerings on revenues as N is exogenously determined. The value of postponement calculated using the profit maximisation strategy, which is 20.24%, can be seen as a more reasonable assessment of the actual postponement benefits. Furthermore, the existing trade-off between product variety and lead time is also neglected. Under the integrated approach, the parameters c_x and c_t representing how sensitive customers are to the deviation between their ideal taste and the feature offered and to the delivery lead time would obviously determine the profitability (see Section 15.4.2 for more details). Under the cost minimisation strategy, however, the importance of these parameters is invisible.

In summary, through these numerical examples we show that the integrated model we develop allows us to better explain how postponement results in increased supply chain profitability by having giving us clearer visibility regarding the interaction among all the factors attributed to the production-inventory as well as the marketing functions.

15.4.2 The Impact of Postponement on Profitability

We now present numerical results in assessing how postponement enhances the manufacturer profitability. It is also our aim to examine how the profitability level is affected by different parameters. A numerical experiment was conducted to achieve this purpose and the list of parameter values used in the experiment is presented in Table 15.3.

Table 15.3 presents all the parameter values used in the experiment. The aggregate demand rate is fixed at $d_0 = 6$ in this experiment. The reservation price is also fixed at $r = 600$, which we consider large enough to ensure that the net utility is always greater than zero and so all customers will buy a product. We fix the unit production cost for MTS and DD at $c_{\mathrm{MTS}} = c_{\mathrm{DD}} = 100$. As stated earlier, setting the same unit production cost for the two configurations will constitute an upper bound of the value of postponement. Five different values of m are used for the production rate. To study the effect of the sensitivity of customers to the delivery lead time and the deviation from their ideal preference, four different values of c_t and c_x are tested in this experiment. Further, four values are also used as the product proliferation cost. The combination of all these parameter values makes in total 1280 problem instances. We summarise the main findings as follows.

Table 15.3 The parameter values used in the numerical experiment

Parameter	Unit	Number of values	Values
d_0	/ time unit	1	5
r	£	1	600
c_{MTS} , c_{DD}	£	1	200
m	/ time unit	5	6, 7, 8, 9, 10
h_i	£/unit/time unit	4	5, 10, 15, 20
c_t	£	4	20, 40, 60, 80
c_x	£	4	50, 100, 150, 200
k	£	4	5, 10, 15, 20

15.4.2.1 Aggregate Comparison

Table 15.4 summarises the overall average values for different measures that could be of interest when comparing the two configurations. The results show that postponement leads to increased profitability in general. The value of postponement, measured by *%PROFIT GAIN* has an average of 8.4% and can be as high as 37.8%. However, it is also notable to mention that the dominance of DD over MTS is not observed in the whole problem instances. There are six particular instances in which MTS brings greater profits than DD, which reflects the detrimental effect of postponement. Parameters of these instances are characterised by the smallest c_x (= 50), the highest c_t (= 80), the smallest hi (= 10) and the highest k (= 20). It is also shown that the average optimal number of products DD can offer is 6.44, while MTS can only offer 4.41 products. While the product proliferation cost is the same for the two configurations, increased flexibility offered by postponement allows the manufacturer to enhance the customisation level by offering more product variants. Postponement also leads to a higher average optimum price that can be charged to customers. Although the difference between the average prices for the two configurations appears to be insignificant, for some instances we may find that the difference is much larger. We shall discuss this later in more detail.

Table 15.4 Aggregate comparison between MTS and DD

Output measures	MTS	DD
Maximum profit	1851.05	1895.77
Minimum profit	1192.96	1555.01
Average profit	1634.54	1764.91
Average number of products	4.41	6.44
Average price	567.91	575.50

15.4.2.2 The Effect of Production Rate (*m*)

The effect of production rate on the benefit of postponement is illustrated in Figure 15.4. As the demand is held constant, this also represents the effect of the capacity utilisation level. It is shown that while the average profits for the two configurations increase in the production rate, the benefit of postponement appears to be diminishing. This finding is in line with what is reported in Wong *et al.* (2009). For a very congested system in which the production rate is low, the relatively high benefits of postponement come from significant differences in total stocks held by the MTS and DD configurations. For MTS, we observe that the reduction in total stock across all product variants caused by increased production rates has more profound effects in comparison to the reduction of the total stock of generic component in the DD configuration.

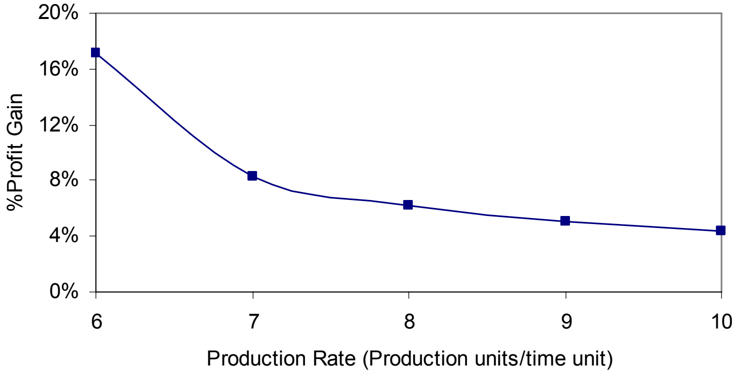

Figure 15.4 The effect of production rate on % profit gain

15.4.2.3 The Effect of Unit Inventory Holding Cost (h_i)

Our experiment shows that the effect of unit inventory holding cost on the value of postponement is in accordance with what is reported in most of studies on postponement (*e.g.*, Gupta and Benjafaar 2004, Wong *et al.* 2009). As illustrated in Figure 15.5 the value of postponement is increasing with the unit inventory holding cost.

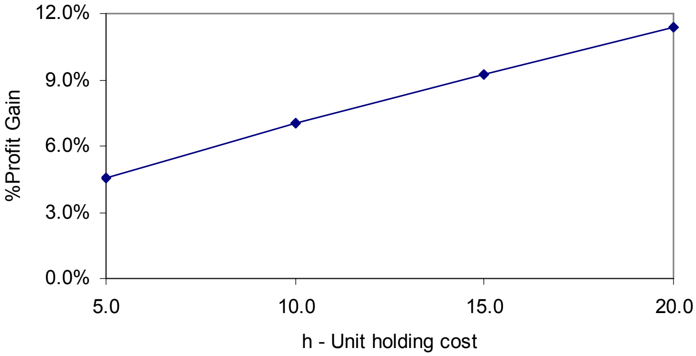

Figure 15.5 The effect of unit holding cost on % profit gain

15.4.2.4 The Effect of Customers' Disutility on Waiting (c_t)

Figure 15.6 shows how the relative profit differences between MTS and DD as a function of the customers' disutility cost of waiting. It is shown that the average profit gain first increases and then decreases. Figure 15.7 is also provided to depict the average profits for the two configurations. For the DD configuration, the average profit steadily decreases in the range of cost values used in the experiment. But for the MTS configuration, the average profit first decreases before reaching a plateau. When c_t increases, the MTS system will reduce the lead time by holding a higher inventory level. There is, however, a point where the inventory level is sufficiently high to allow a zero lead time. From this point on, the profit of MTS will not change while the profit of DD still decreases. This observation suggests that postponement benefits would vanish when customers are more sensitive to delivery lead times. In the extreme case where customers really want to get their product instantly (and customised attributes are less important), postponement is obviously not a recommendable strategy.

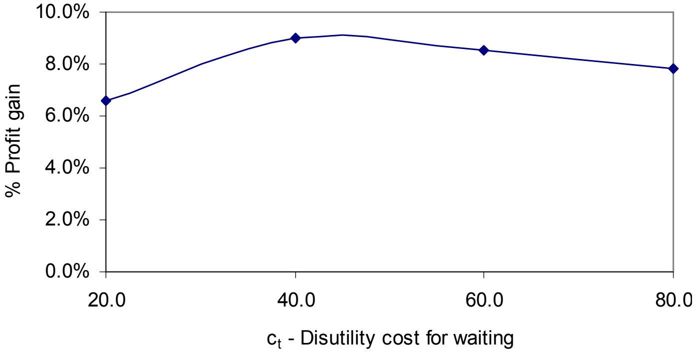

Figure 15.6 The effect of waiting cost on % profit gain

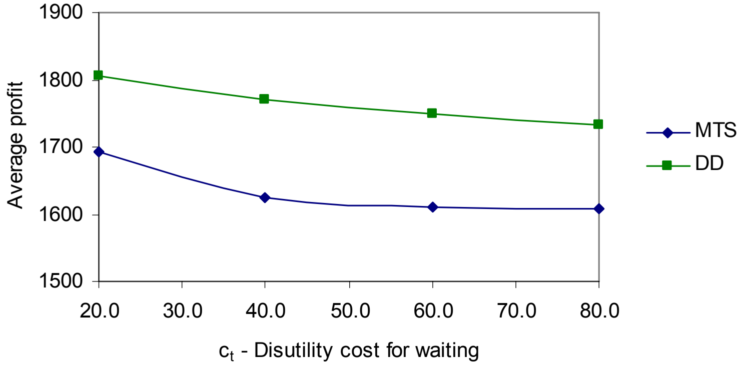

Figure 15.7 The effect of waiting cost on average profit

15.4.2.5 The Effect of Transportation Cost (c_x)

Figures 15.8 and 15.9 are presented to explain the effect of transportation cost on postponement benefits. Recall that the transportation cost represents customers' dissatisfaction in not getting their ideal preferences. As depicted in Figure 15.7 the profit gain is higher when the transportation cost increases. By holding the common intermediate goods and executing the final customisation later, the DD configuration would enable minimising the customers' transportation cost by offering more product variants in the market than the MTS configuration, as depicted in Figure 15.8. The proven success of Dell suggests that to a certain extent PC customers seem to have good appreciation of the introduced customisation feature, reflecting the possible existence of high transportation costs. But there are also applications in mass customisation, *e.g.*, customised shoes (Berger 2003) where we conjecture that these customised products serve only a niche market and the total market is still dominated by the mainstream products. It is not well understood whether the difference in the adoption level of the mass customisation concept is due to the difference in the transportation cost. Empirical research that attempts to assess and compare the transportation cost for different products would certainly be worthwhile.

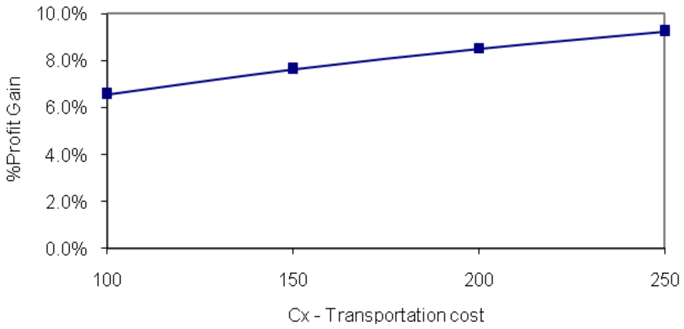

Figure 15.8 The effect of transportation cost on % profit gain

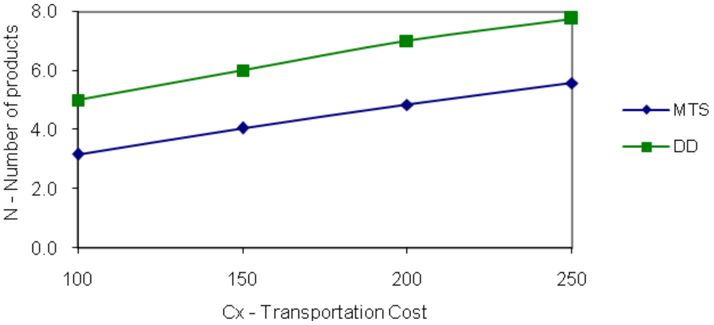

Figure 15.9 The effect of transportation cost on the number of products

15.5 Conclusions

Postponement has been recognised as an important technique that has great potential in creating supply chain improvement through reduction in uncertainty and cost while satisfying customer needs. By restructuring the production and distribution of products in such a way that the customisation of these products is made as close as possible to the point when the demand is known, postponement can greatly improve the flexibility capabilities of the firms that employ it. Today, where more and more industries move towards creating markets of one, such significant flexibility improvement is important in accommodating mass customisation strategies.

This chapter is an attempt to obtain a better understanding of postponement benefits by developing a new perspective that considers cross-functional implications and coordination issues. In contrast to the vast majority of existing studies on postponement where the focus has been on the production-inventory system, the new perspective we developed tries to address the important alignment between the production-inventory and marketing functions. Under this integrated perspective, we are able to get a more complete view on how postponement may enhance firms' profitability by capturing interactions among many factors including inventory, lead time, price and product variation.

The stylised models presented in this chapter allow us to find out how postponement benefits could be different when assessed by the proposed integrated approach as opposed to the traditional production-inventory focused approach. The evaluation based on the cost minimisation strategy used under the production-inventory focused approach would reveal how much inventory cost savings can be gained by employing postponement. However, such an evaluation is helpful only when the main intent is to evaluate postponement benefits under exogenously predetermined demand and product variety. As such, this traditional approach is not capable of reflecting the more realistic and complex problem that may involve marketing-related aspects in the sense that customers' demands are actually influenced by price, lead time and product variation. The proposed integrated approach is able to overcome such limitations. Through numerical examples we show that the inventory cost minimisation problem is not equivalent to the profit maximisation problem. In extreme situations such as in markets where customers are sensitive to delivery lead time, the benefit of postponement in terms of inventory cost savings may need to be offset by some costs to compensate longer lead times, which can be reflected in lower prices. This kind of observation is only possible if we use the integrated approach.

Through the numerical experiment we demonstrate how different system parameters may have an impact on the benefit of postponement measured by the relative difference of profits for the MTS and DD configurations. It is shown that the production rate increase has a positive effect on the average profit of the two configurations. However, the benefit of postponement appears to diminish as production rate increases. Our research also confirms what has been reported in most of the postponement studies: the benefit of postponement increases in line with unit inventory holding cost. This suggests that postponement is more beneficial when products have high inventory costs.

The effects of the marketing factors are also examined. The results show that the average postponement benefit first increases and then decreases with the customers' disutility cost for waiting. This observation suggests that postponement would not be appropriate in a market where customers are highly sensitive to delivery lead times.

Finally, the effect of the transportation cost on the value of postponement appears to be obvious. The value of postponement is higher when the transportation cost increases. As the transportation cost represents the customers' dissatisfaction with not getting their ideal preferences, postponement would allow the DD configuration to minimise customers' transportation costs by offering more product variants in the market than the MTS configuration. All in all, the results obtained from our study are still in line with mainstream findings suggesting that postponement may lead to significant benefits. However, the integrated approach allows us to have a better view, especially when the prevalent lead time *versus* variety trade-off comes into play.

Like all models, ours has limitations. First, our results rely on the assumption that customers are heterogeneous only in terms of their ideal preference. Customers are assumed to be homogeneous in terms of their reservation price, transportation and waiting costs. In situations where customer heterogeneity is not only limited to the ideal preference, some key insights may change. For example, if consumers are allowed to have uncommon reservation price for their ideal products, the full market coverage may no longer be optimal. Second, our model ignores competition. In particular, our model is concerned with postponement evaluation in that it ignores the existence of competition between standard and customised products in the market. We believe that incorporating an extended customer heterogeneity and product competition may prove to be fruitful in future.

Some other opportunities for future research arise from this work. As we stated earlier, empirical research to assess different parameters in real settings is a challenge. In particular, research to estimate customers' disutility associated to lead time as well as to the deviation between their ideal taste and what is offered would be very valuable. This research would not only be useful in identifying postponement benefits on a more realistic scale, but also in getting a better explanation of why some mass customisation practices are successful while others are not. Another opportunity is to extend the concept of product differentiation. While this chapter focuses only on horizontal product differentiation, research that also considers vertical differentiation certainly warrants attention. This is true as for many products such as electronic gadgets, PCs or bicycles; customisation would involve both vertical and horizontal differentiation.

Last but not least, it may be worth highlighting that this chapter represents one of the very few studies addressing issues that lie within the interface of the operations management and marketing disciplines. We believe that, particularly in the context of mass customisation, much work still needs to be done and most of it would require multi-disciplinary efforts involving expertise from these two domains.

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Part IV
Mass Customization: Case Studies

Chapter 16
User Participation Within Virtual Worlds

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Abstract This chapter's objective is to highlight the potential that virtual worlds and their best known ambassador Second Life offer in the area of mass customization. After an introduction to virtual worlds in general, three case studies of companies (Dell, Philips, and Sears) applying mass customization and related techniques in virtual worlds will provide an overview of the potential of this new medium. Results show that both company representatives and virtual world consumers are excited about the idea of virtual mass customization, but that several problems and limitations still have to be overcome.

Abbreviations

CEO	Chief executive officer
HBR	Harvard Business Review
L$	Linden Dollar
MC	Mass customization
PC	Personal computer
RL	Real life
SL	Second Life
VP	Vice president
VUC	Virtual universe community

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16.1 Introduction: From Traditional *via* Electronic to Virtual Mass Customization

Manufacturers in the 20th century were able to choose between two distinct strategies: (1) being a cost-efficient mass producer with limited or no variety, or (2) offering highly customized and often expensive products resulting from a craftsmanship-like approach. Toffler (1970), however, questioned the distinctiveness of these two strategies and Davis (1987, p. 169) introduced the term mass customization (MC) to describe the oxymoron of mass producing customized products, which was subsequently elaborated on in publications such as Gilmore and Pine (1997) and Pine *et al.* 1993, 1995. Certainly the basic idea behind this approach is not revolutionary, since customers have always been able to customize certain mass-produced products by choosing from predefined modules, for example, when ordering a kitchen consisting of parts adapted to specific characteristics of the room or the cooking practices of the user (Kaplan 2006). However, only recently new manufacturing techniques and advances in information and communication technology, such as the Internet, have made MC a viable option for a broad range of products, as traditional MC has evolved towards electronic MC (see Kaplan and Haenlein 2006 for more detail on the differences of traditional and electronic MC).

In theory, due to these new techniques and technologies, there are several types of products that can be customized nowadays “with production cost and monetary price similar to those of mass-produced products” (Kaplan *et al.* 2007, p. 102). To date, many of these opportunities have not yet been put into practice. Although there is still enormous potential for traditional and electronic MC, there might be a new trend in MC on the horizon – virtual MC in so-called virtual worlds. These computer-based simulated environments, whose most prominent representative is certainly the virtual social world Second Life (SL)[2], are intended for its users to inhabit and interact in the form of personalized avatars. Avatars are the virtual persona that people use to communicate with each other in virtual worlds (see Holzwarth *et al.* (2006) for a more detailed discussion of avatars). These avatars, which may have any appearance desired by the user, can perform all activities familiar from their real life (RL). Examples of such activities might be visiting night clubs, making friends, or customizing, for example, a virtual kitchen (in the same way as a real person would customize a real kitchen in the case of traditional MC). In 2006, Hemp claimed in his HBR article to be impressed that in virtual worlds the concept of MC was already wildly popular with avatars choosing to customize many elements of their characters (Hemp 2006). Moreover, Joseph Pine, pioneer in the field of MC, expressed his excitement about “all the commercial activity going on in Second Life […]. Now the opportunity exists to mass customize virtual offerings to the avatars of real people!” (Piller 2007, p. 6).

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[2] “Second Life”, “Linden Lab”, “Linden”, and the abbreviation “SL” are trademarks of Linden Research, Inc.

The purpose of this chapter is to analyze the potential that virtual social worlds and their best known representative SL offer in the area of MC. Specifically, the objectives are twofold: first, the reader will be introduced to virtual worlds in general and SL in particular. Second, three case studies of companies applying MC and related techniques in virtual worlds, that is, the cases of Dell, Philips, and Sears, will provide an overview of the potential of this new medium, leading to key insights and lessons on employing MC in a virtual environment.

16.2 Literature Background: About Virtual Worlds and Virtual Mass Customization

This first section will detail five important issues that managers should be aware of concerning virtual worlds and virtual MC. First, virtual worlds are a special type of social media. Second, there are several different types of virtual worlds. Third, SL is the most prominent among them. Fourth, consumers of SL do not see it as a game but rather an extension of RL. Finally, some opportunities for virtual MC and its potential will be identified.

16.2.1 Virtual Worlds Are a Special Type of Social Media

Virtual worlds are part of a larger group of Internet-based applications called “social media” being defined as “a group of Internet-based applications that build on the ideological and technological foundations of Web 2.0 and that allow the creation and exchange of user generated content” (Kaplan and Haenlein 2010, p. 61). Social media can take many forms, including blogs and microblogs (*e.g.*, Twitter), content communities (*e.g.*, YouTube), social networking sites (*e.g.*, MySpace), collaborative projects (*e.g.*, Wikipedia) and virtual worlds. Common in these applications is that content available through them is created, maintained, and updated by individual Internet users and provided to other users, often free of charge in an altruistic manner. This makes social media different from traditional web pages such as those of eBay or Yahoo where the company decides upon most of its content on their sites. Social media is based mainly upon user-generated content. Within social media, virtual worlds have three characteristics that differentiate them from other social media types (Kaplan and Haenlein 2009c). First, virtual worlds allow users to interact with others in real time, *i.e.*, a conversation within SL is identical to one in RL – with the exception that it is not conducted in personal face-to-face format. While there are some social media sites such as Facebook that allow for real-time interaction, this is not their routine application. Usually, content on pages like YouTube, MySpace, Wikipedia, and also Facebook is posted and then consumed by others with a time delay. Second, virtual worlds allow users to create fully customized virtual self-presentations in the form of avatars. Although a YouTube user potentially creates some form of image within the community by choosing the types of videos posted, avatar customization within virtual worlds is far more flexible. If desired, a user of virtual worlds can create an avatar that very closely resembles the real appearance of the associated user – or that of a very different person. Finally, while content communities, blogs, and collaborative sites are two-dimensional (*i.e.*, focused on content sharing), avatars within virtual worlds have the possibility to explore their virtual environment in three dimensions. Therefore the terms Web 3.0 and Web 3D are often used in connection with virtual worlds in order to describe the new (three-dimensional) element virtual worlds add to the World Wide Web.

16.2.2 Virtual World Does Not Equal Virtual World

Within the group of virtual worlds, it is necessary to differentiate between two different forms, namely virtual game worlds such as "World of Warcraft" and virtual social worlds such as "Second Life" that are the focus of this chapter (Kaplan and Haenlein 2009c). Within virtual game worlds, where the main aim is to play a game, users are usually required to follow stricter rules that govern their behavior and avatar customization. Virtual social worlds such as SL, on the other hand, do not pose any restrictions on the way avatars can behave or interact. However, the main difference between these two forms of virtual worlds lies in the fact that virtual game worlds often do not allow one to engage in economic activities with other users within the world, including the sale and purchase of content. Instead, such activities are conducted using means from outside the virtual world, such as the online auction house eBay. By contrast, virtual social worlds are real economies. Usually in virtual social worlds residents hold the copyright on all content they create and are allowed to sell this content to other users in exchange for virtual money. In the case of SL, the virtual currency is called the Linden Dollar (L$) and avatars can either exchange RL currencies for such Linden Dollars *via* the SL Exchange at a floating exchange rate that is approximately stable at 270 L$ *per* US$ or derive virtual income by managing businesses, working in stores or providing entertainment services. Money that has been earned in such a way can either be kept in one of SL's banks (in exchange for interest payments) or re-exchanged into RL currency. For some users income earned within SL even complements their RL salary. According to Linden Lab's official economic statistics, there were 68,108 SL residents during April 2009 who had a positive monthly Linden Dollar flow, with 214 of them earning more than 5,000 real US $[3]. Finally, by looking at Anshe Chung (RL name Ailin Graef), a virtual real estate agent, who has become the first US $ millionaire through her activities in SL, one grasps the

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[3] (in US $ *per* SL resident) < $10: 38,553 / $10 to $50: 18,425 / $50 to $100: 3,895 / $100 to $200: 2,486 / $200 to $500: 2,410 / $500 to $1,000: 1,072 / $1,000 to $2,000: 649 / $2,000 to $5,000: 404 / > $5,000: 214.

potential of this virtual economy (Hof 2006). This achievement is all the more remarkable because the fortune was created over a period of roughly 3 years from an initial investment of US $9.95 (cost for a SL account). Today Anshe maintains RL offices in North America, Europe, and China with over 80 full-time employees, having expanded her activities to other virtual worlds such as IMVU and There.com.

16.2.3 Second Life Is the Most Prominent Virtual World

Founded and managed by the San Francisco-based company Linden Research, Inc., SL is arguably the most well-known virtual social world as a result of extensive coverage in the business and popular press. Similar to other virtual social worlds, SL users can enter the virtual environment through a downloadable client program in the form of personalized avatars. As explained above, avatars are not a new concept and they have previously been discussed in academic literature (*e.g.*, Holzwarth *et al.* 2006, Wang *et al.* 2007). However, until now, the focus of these analyses has mainly been on their function as sales agents in business-to-consumer relationships. While avatars may fulfil such a role within SL (*e.g.*, when working as sales clerks in virtual stores), their main purpose in SL is to provide a form of self-presentation within the virtual environment. This is similar to that which has been discussed in the context of users' motivations to create personal websites (Schau and Gilly 2003). In line with consumer culture theory (Arnould and Thompson 2005), SL provides users with the possibility of constructing an alternative identity that can either be a replication of their RL self, an enhanced version of their real self with improvements in certain attributes or a completely different self. Compared to other virtual worlds, users in SL face no restrictions regarding the type of self-presentation that can be created, which leads to avatars appearing in any form possible and surrounding themselves with any object of their liking. Communication between avatars is most often conducted in written format (either chat or instant messaging), although a voice-chat option was introduced in August 2007. To move from one location within SL to another, avatars can walk, fly, teleport, or ride in vehicles such as cars, submarines, or hot-air balloons. Residents also have the option of purchasing real estate within the virtual world, ranging from small lots ($512\,m^2$) to whole regions and private islands, on which they can build houses for their avatar to live in and which can subsequently be equipped with furniture and appliances. Avatar interaction within SL is largely driven by subcultures, *i.e.*, based upon groups of avatars displaying the same interests and leisure activities. These subcultures mirror either RL settings (*e.g.*, shopping malls, nightclubs) or fictional/historical situations (*e.g.*, ancient Rome). Thus avatars can choose between several different experiences such as dancing and flirting in a nightclub atmosphere, having virtual sex in one of SL's red-light districts or experiencing life on an island that replicates ancient Rome.

16.2.4 Second Life Is Not a Game but an Extension of Real Life

One very important fact companies have to understand about virtual social worlds and especially about SL is that we are not talking about video games but rather an extension of RL. This can be justified from two directions: first, many companies such as DELL or Microsoft, as well as other organisation types such as business schools (Kaplan 2009) are already on SL, and many of them take their mission extremely seriously. IBM, for example, is setting up a whole business unit to deal with virtual social worlds. Big Blue is currently one of the biggest real estate owners within SL (the company owns more than 50 islands of 65,536 m^2 each) and has set up a US $10 million project to build a three-dimensional World Wide Web using the SL platform. The company's "virtual universe community" (VUC) is responsible for identifying new business models within virtual worlds and consists of 5,000 employees. IBM uses SL to conduct meetings, provide training and education (especially for new employees), organize events, and develop new products. By early January 2007, more than 3,000 employees had already created their own SL avatar, and 10% of these employees use the medium regularly (Carter 2009). In order to ensure appropriate conduct in virtual and real interactions, IBM have even established a set of virtual world guidelines that are designed to regulate an employee's conduct and appearance within SL. A second justification for virtual social worlds not being just a game comes from looking at the residents themselves: users do not consider SL as a computer game, but as an extension of their RL. Kaplan and Haenlein's (2009a) research shows that at some point, SL users seem to start engaging in activities that span beyond the single usage occasion, *i.e.*, they start making long-term plans of their virtual lives. While at the beginning SL users enter the virtual world in order to interact with other avatars on a day-to-day basis, after a certain while residents start to make plans, *e.g.*, how to decorate their virtual homes or what other virtual items they could need in the future. According to Haenlein and Kaplan (2009) this effect is most likely influenced by increasing usage intensity (duration of time spent on SL *per* visit) or consumption frequency (number of times entering SL). Often the planning horizon that underlies SL usage even goes beyond the actual time spent within the virtual social world, *i.e.*, SL residents also think about their virtual lives when in the real world. SL residents want to be taken seriously and often only see minor (sometimes even no) distinctions between their real and virtual lives. All the corporate activities on SL together with the residents' serious use of it, lead to an economic importance of SL that has the characteristics of a real economy rather than those of a simple computer game. In April 2009, a total of over 27 million transactions between L$ 1 (~ 9.6 million transactions) and over L$ 500,000 (430 transactions) took place[4], with 976 residents spending more than 1 million Linden dollars on SL (~ US$ 4,000) during this month (Linden Lab, official economic statistics).

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[4] Official SL resident transactions by amount during April 2009 according to Linden Lab's official economic statistics: 1L$: 9,599,106/2-19L$: 5,700,724/20-49L$: 2,814,340/50-199L$: 4,642,112/200-499L$: 2,316,175/500-999L$: 948,704/1,000-4,999L$: 970,184/5,000-19,999L$: 240,093/20,000-99,999L$: 51,444/100,000-499,999L$: 4,769 / >=500,000L$: 430.

16.2.5 Second Life Offers Several Opportunities for Virtual Mass Customization

Before going into the possibilities of MC on SL, two areas of virtual MC outside virtual social worlds will be presented. This shows that virtual MC is not just a fad as a result of virtual worlds like SL having gone through a hype cycle recently (with a peak in 2006/2007), but that virtual MC has high legitimacy on its own.

A first example of virtual MC comes from the fashion industry that has started to use avatars as virtual mannequins (Yoo 2007). In order to create the customized avatar as one's personal mannequin, either a customer's body will be scanned with advanced technology or alternatively he/she types in his/her measurements into the computer. Using the avatar, customers can then virtually try on clothes to see how they suit them, and ultimately buy the real versions. Shinsegae, a major South Korean department store franchise, offers customers the possibility of dressing three-dimensional avatars of themselves that include their precise body measurements. Interested customers enter the 3D scanner resulting in a customized virtual replication on a life-size screen. The customer then scans the item tag he/she wants to try on and it appears on his/her avatar. The system also lets the customer select from a variety of other clothing options such as changing the colour or size of the chosen item. After a customer has been scanned the information is stored in the system for future purchases. An extension of this option is in the planning stage for the Shingsagae e-commerce site. This might be very profitable to the online fashion retailer since many people avoid buying clothes over the Internet because they cannot try them on. According to Carter (2009), quoting a study conducted by Lands' End, virtual mannequins increase the conversion rate by 26%. The same study also showed that "the average order value was 13% higher for shoppers who used the virtual model technology than shoppers overall" (Carter 2009, p. 398).

A second example of virtual MC can be found in the automotive industry. "Today's customers want to have their dream car the very next day and be able to change options right up until the last minute if possible", says Harald Gmeiner, Siemens Global Account Manager for Volkswagen (Kunze 2008, p. 66). In April 2008, Siemens teamed up with Volkswagen and presented today's state-of-the-art in technology at the world's largest industrial fair in Hannover, Germany. Their objective was to demonstrate the opportunities that result from combining real with virtual factories. Using the Volkswagen Tiguan, Siemens replicated the entire factory process chain at a stand measuring 160 m in length with some of the elements presented being real while others such as the press plant were presented virtually. The aim, which has not yet been achieved, is a complete virtual process chain, *i.e.*, the exact replication of steps to be taken in a specific order that lead from an initial to the desired final state of a car. The advantage of such a virtual description of all important information belonging to a product's lifecycle would make it possible to change elements in the manufacturing and production process even after production had already begun. Such a virtual process chain will move

Siemens much closer to its vision of pure MC (Kaplan and Haenlein 2006). Gmeiner stresses the potential of virtual MC by pointing out "While it's true that passenger car customers currently have the greatest tendency to request product alterations until shortly before delivery, we'll definitely soon be seeing this phenomenon in other sectors as well" (Kunze 2008, p. 68).

It is not difficult to see how both approaches, the virtual mannequin or the virtual automotive process chain, could be integrated into a virtual social world – actually it would make more sense to implement them there. A lot of companies already use SL in order to apply concepts such as user participation and MC. Dell had avatars customize virtual PCs and, if they wanted, they could have a real version of the virtual replica sent to their RL homes (Krazit 2006). Sears teamed up with IBM in order to offer the possibility of virtually customizing a kitchen for SL residents (Todé 2007). Starwood Hotels and Resorts used user participation to first build their "Aloft" hotels virtually within SL to obtain a better understanding of which features might be important to users before launching them in RL. According to Brian McGuinness, Starwood VP, the virtual test phase led to several design changes including the decision to build radios in the guest room's showers (Fass 2007). Philips used avatars' feedback for co-designing and co-creating their RL products (Bal 2007). Finally in 2007, the association "Accomplir" asked Parisians to participate in a competition (winning prize of 125,000 Linden Dollars) to design a new park within SL that was supposed to inspire the construction (starting in 2013) of the RL park in front of "Les Halles" shopping mall, located in the very heart of the real Paris (Le Parisien 2007).

16.3 Analyses and Propositions: Dell, Philips, and Sears as Pioneers of Virtual Mass Customization

At present there are several corporate activities taking place in SL along with many companies trying to integrate the customer into the production process. To gain insights and potential key lessons, three companies employing MC techniques are looked at in detail. In line with Eisenhardt (1989) companies were chosen that display different aspects of virtual mass customization and therefore potentially offer most insight. After detailed research in the business press and on specialized blogs, forums, and company websites, the three companies Dell, Philips, and Sears were identified as the most promising. Analyses mostly rely on own ethnographic observations (Kozinets 2002) as well as business press articles and official press releases published by these three corporations. Regarding Dell, furthermore an in-depth interview was conducted (45 min, November 2008) with Laura P. Thomas who is in charge of Dell's SL strategy. Additionally, in the case of Dell and Philips the author analyzed *verbatim* (being part of a bigger research project) originating from avatars, having visited the respective company presence on SL (Dell: 142 *verbatim* / Philips: 59 *verbatim*) and giving a general impression of the companies' SL strategies.

16.3.1 Dell: Virtual Mass Customization of RL Products

In November 2006, Dell was one of the very first corporations in SL to set up a virtual flagship store. From the outset, Dell considered SL primarily as a potential channel for getting in touch with its end-customers and used it as a tool for advertising, communication, and virtual commerce. Dell maintains four connected islands within SL to regularly organize events that complement or mirror RL advertising/communication campaigns. For example, in January 2007 Dell organized a virtual premier party for Universal's movie *Evan Almighty*, which carried Dell's product placement and co-branding in RL. Four months later, in April 2007, Dell extended its "Plant a Tree for Me" program into the virtual world and gave residents the opportunity to grow virtual saplings on dedicated SL areas. In January 2008, the launch party for Dell's new Crystal monitor line at the Consumer Electronics Show in Las Vegas was mirrored in SL in the form of a virtual launch party. While such activities ensured constant coverage of Dell within virtual and real media, Dell's unique strategy also consisted of using SL as a tool to distribute its customized RL products (Zehr 2006).

At the very beginning of its activities Dell distributed free virtual equivalents of its RL XPS personal computer line to SL residents in the context of an advertising campaign. These PCs were able to perform simple tasks, such as alerting a resident when one of his/her friends was nearby. After this inauguration event, Dell also offered residents the possibility of fully customizing and personalizing their PCs within the Dell Factory on Dell Island. SL residents could customize their new virtual or a RL Dell PC by performing some simple tasks at a virtual configuration table. In case the avatar decided to buy a RL version of the virtually mass-customized computer, he/she would be linked to the Dell.com e-commerce system in real-time where he/she could buy a real PC in $US. If the avatar decided not to buy an RL version, he/she could keep the virtual version for free. "Second Life allows us to connect with customers in a rich and robust way" (Krazit, 2006) said Ro Parra, senior vice president and general manager for Dell's Home and Small Business Group.

The virtual MC experience was ended after a 12-month trial period due to lack of sufficient profit potential as Laura P. Thomas (alias Pyrrha Dell), the person behind Dell's SL strategy, reported in an interview conducted with her in November 2008. According to Ms Thomas, Dell's initial motivation for entering SL was the wish to be on the forefront of a new technology and to use the virtual world as a platform to explore the possibilities offered by a three-dimensional version of the World Wide Web. In this context the virtual MC application on Dell Island was considered as a trial for an alternative form of e-commerce. The integration of the Dell Factory with e-commerce applications generated substantial costs that were not compensated by associated revenue as the proportion of SL residents actually conducting a purchase was miniscule. As highlighted by Ms Thomas, the current SL population sees the world mainly as a place for fun and diversion, and product purchases are not on the minds of most users. Although she sees a promising potential for virtual commerce (v-commerce) in future, current technical difficulties make it a costly endeavor. Ms Thomas highlighted the need to conduct all actual transactions outside of the virtual world as the exchange rate of the Linden Dollar remains too volatile to accept in exchange for RL products.

Similar opinions can be found in some of the 142 avatars' *verbatim* resulting from the research study commenting on Dell's SL virtual MC opportunity. Overall, the idea of using SL as a sales channel for RL customized products received substantial positive feedback ("I really liked how you could build your own computer in the Dell Factory and then go online to purchase it. Very neat idea!"). However, avatars also highlighted that the medium might not (yet) be suitable for such usage ("I was amused with the feature that you could build your own Dell computer in SL and then link to a website where you could actually buy that computer in RL – even though I wouldn't consider buying a Dell computer from SL, it was a good concept and has potential to develop").

16.3.2 Philips: Understanding the Consumer First, Then Integrating Him in the Design Process

Together with Rivers Run Red, one of the leading virtual world design agencies, in April 2007 Philips opened a SL presence located on Our Virtual Holland Island. In June 2008 Philips moved its SL presence to its own island "Philips Design Experiences". On this island residents virtually test new concepts and participate in the co-creation and the co-design of Philips products. To do so, avatars register at the Philips stand named "Co-creation Experience" and join the "Design Friends Group". In consequence, residents decide upon the colors, shapes, functions, and other features of Philips' consumer electronics that they would like to purchase. At the conclusion of each project participants are rewarded with incentives. Besides these collaborative activities, avatars are asked to share their observations and daily activities in SL with Philips employees (Bal 2007, Bal and Jorden 2006, Miendlarzewska and Kozlov 2009).

Although not yet directly applying MC techniques on SL, Philips makes use of the related area of user innovation (von Hippel 1982, 1998). "This will allow Philips Design to find new ways of relating to end users. Having such direct feedback can significantly enrich the design process and lead to innovative and surprising end results. This fits with the Philips Design philosophy that design should be based around people and grounded in research. It also corresponds to Philips Design's firm belief that the future of design lies in the co-creation of products" (Bal and Jorden 2006). According to Philips Vice President, Andre Rotte, who is responsible for the SL initiative, the two big advantages of co-creation and co-design in virtual worlds are, first, the financial benefits and, second, the increased access to potential clients (Schouten 2007). The SL initiative is successful as one can read in a Philips press release stating that avatars enjoy "their involvement in this method of research, continuing to provide feedback even after one study ended" (Bal 2007).

Besides “Leveraging Second Life as an environment for co-design” stated by Philips on their web presence, the consumer electronics company wants to “to truly understand what Second Life is”. Or as Slava Kozlov, Senior Researcher Consultant with Philips Design, describes it “Our aim was to explore and learn about Second Life and its people. Our attitude was to understand and learn, not to sell, because people can smell it when it is otherwise” (Miendlarzewska and Kozlov 2009, p. 12). Thus Philips’ initiative of the “Co-creation Experience Stand” and the “Design Friends Group” is principally “aimed at further understanding people’s motivations and desired experiences in virtual immersive environments” (Philips Design 2007). Before integrating the consumer in the design and production process, Philips made it its core objective to get a deep comprehension of virtual worlds. The Philips research team dealing with virtual worlds works on questions such as what SL really means, why people are driven to live in a virtual social world, and what the link is between SL and RL (Kozlov and Reinhold 2008). This shows Philips’ long-term vision for virtual worlds and its consideration of SL as a serious consumer channel and not as a game, further underlined by Justin Bovington, CEO of Rivers Run Red, who pointed out that Philips’ “commitment to establishing a presence in this virtual world also helps to legitimize Second Life as a serious space. It means that Philips Design is thinking about the virtual world for the longer-term” (Bal and Jorden, 2006).

As with Dell’s approach to virtual MC, several of the 59 avatars participating in the previously mentioned research project said they liked the idea of being integrated in the production and design process on Philips’ SL presence. However, they also voiced critique and regretted the unclear marketing positioning and smallness of the island, and above all the emptiness of the presence: “I like the concept of co-creation and co-design, but the island itself seemed to me a bit too busy, with too many different things. Didn’t seem easy to find what exactly Philips is about in SL”; “I thought it was a pretty small sim, but I liked the idea of being involved in the creation”; “Empty! I would have expected more from Philips. Is it only an advertisement?” Summarized by Slava Kozlov, Philips’ experience on SL clearly shows that although user integration in virtual worlds is well appreciated by avatars, there is an immense necessity to first understand this new and little known environment: “You can start with a vision in your mind, but be ready that the final version may be significantly different from what you imagined. And this was also a learning for us: we were happy to see the community emerging, happy to see people’s willingness to co-create” (Miendlarzewska and Kozlov 2009, p. 17).

16.3.3 Sears: Too Much or Not Enough Reality for a Virtual World?

At the Consumer Electronics Show in Las Vegas in January 2007, Sears launched a prototype virtual 3D store, called Sears Virtual Home, which resides on an IBM island within SL. In the introduction, the example of a customized kitchen was taken in order to show that customers have always been able to customize certain mass-produced products by choosing from predefined modules and that MC is not a completely new concept. Today, with new manufacturing techniques and advances in information and communication technology MC has become a viable option for a wider range of products. On Sears Virtual Home traditional MC is transformed into a virtual version of MC. Consumers in the form of avatars can experiment by changing the color of the cabinets and worktops in a virtual kitchen, explore various home theatre systems in 3D, and learn how to organize their garage by virtually customizing storage accessories. The virtual showroom replicates in 3D the custom design tools already available on www.sears.com. Consumers can order the virtually mass-customized items from Sears Virtual Home by clicking through to Sears.com for their RL home (Allegrezza 2008, Facenda 2007, Quinton 2007).

In an interview, Paul Miller, senior vice president at the Sears Holdings, stated that "The Sears Virtual Home combines the best of virtual worlds and 3D environments so customers can experience Sears' products in a way that is closer to Real Life" (Todé 2007). In the same interview, he further notes that "Providing customers with the best possible shopping experience is very important for the company and it is always looking for new and exciting ways to present products and services" (Todé 2007). In the future, Sears plans to offer its customers the possibility of using avatars to replicate their exact room dimensions and experiment with completely redesigning their kitchen by selecting appliances, tools, and furniture. Additionally, avatars would be able to have friends, family members or personal designers join them in the virtual showroom to give their personal advice (Quinton 2007).

However, Sears seems to be in a dilemma. On the one hand their SL presence might be too real for a virtual world. In the end a virtual world may ask for more than just an exact replication of the reality. If somebody is leaving the real world for a virtual one, do they not desire to do things that they could not do in their RL? Would they not rather prefer a kitchen with functionalities only possible in fantasy? Or as one can read on a specialized retailing blog: "Do you really want to create a virtual house furnished by Wal-Mart, Home Depot or Sears and wear clothes from the Gap? If the sky is the limit, why wouldn't you want to wear an Armani suit or a Versace dress, while you sip the finest champagne?" (Shoppingblog 2007) On the other hand, Sears is not yet close to an exact replication of reality. At the moment it does not seem to be real enough. Another visitor to Sears's presence on SL, disappointed about the small number of modules to choose from, points out: "You can choose from about three kitchen styles, and three different cabinet styles. Oh – and two different worktops. Picture what a Flash developer might have created back in 1997, for the Internet. It's almost that good" (Ohrt 2007). Kaplan and Haenlein's (2009b) research gives some insights into this dilemma. Their qualitative analysis of 29 virtual world residents reveals that SL users generally expect that the RL brands available in the virtual environment closely mirror those offered by the company in RL. Only a minority of users seemed to prefer a completely different offering. However, the qualitative interviews did not specify the product type and therefore there might be different expectations if SL residents think of virtual fashion or virtual kitchens. The dilemma in which Sears is situated will be discussed more in the next section.

16.3.4 Key Insights and Lessons: Huge Potential – Just Not Yet

Having looked at three pioneers in virtual MC and co-design in virtual social worlds, the two key insights and lessons are that company representatives as well as SL residents are excited about the idea of virtual MC, but all three companies have encountered problems and limitations with their presences on SL. Table 16.1 summarises key activities, objectives, obstacles, as well as future strategies of the three companies presented above.

Table 16.1 Virtual MC on SL in the examples of Dell, Philips, and Sears

	Dell	Philips	Sears
Current activities	Currently no MC activity. During one year avatars could MC virtual laptops and order them in RL	Avatars are being asked about their opinions on different product features	Avatars can mass customize a virtual kitchen, etc. and order these items from Sears.com
Main objectives	Get in touch with end-customers via virtual commerce; also a (unachieved) profit aim	Enter the virtual world in order to understand avatars and virtual worlds	Offer customers a new and exciting way of buying the company's products
Key obstacles	Avatars and SL were not ready to purchase RL laptops within a virtual environment	Too early to really apply user integration in SL (not priority yet)	Dilemma of how much reality versus virtual (fantasy) avatars desire in a virtual world
Future strategies	At the moment there are no future plans concerning virtual MC or user integration	Increase the use of co-design and co-creation on their SL island	Add more reality to their virtual presence: avatars will be able to replicate their exact RL room dimensions, *etc.*

The first lesson learned is that the corporate representatives of the sample companies are all very enthusiastic about the potential of virtual worlds in general, and MC and co-creation in particular. Moreover, SL residents really like the idea of virtual MC and major corporations going virtual. This is also shown by a study done by Repères (Leclerc 2007), a market research company specializing in SL, which interviewed 1,085 SL residents in March 2007. The results clearly showed that SL residents see RL brands increasing the realism of the virtual world and ensuring SL's longevity as brands generate awareness and wealth. Also, own research, as described above, showed that residents like to have the option of using virtual worlds for tasks other than diversion and chatting. Avatars stated that the fact of being able to customize one's computer in a virtual world and then buy it in RL was a "very neat idea" or that they liked "the concept of co-creation and co-design" in the case of Philips. Purchasing virtual or real customized products through SL or co-designing products is perceived as exciting and new and therefore a potential opportunity for companies.

However, despite the enthusiasm about SL and its future potential for virtual MC and co-designing of products, all three corporations encountered drawbacks or saw limits to virtual social worlds. Virtual worlds are still in their infancy and the potential to earn RL money within SL today is at best limited. The example of Dell clearly shows that there is not yet a large enough market for virtual MC and the number of SL residents interested in using the medium for something other than diversion is still too low. Although residents may not (yet) want to actually buy a laptop through a virtual flagship store, the concerns raised (*e.g.*, lack of security, unintuitive purchasing process) are very similar to those that companies faced at the beginning of the e-commerce era. Apart from the lack of profitability, another drawback is the question of how much reality a virtual MC approach should contain. On the one hand, Sears encounters SL users not being satisfied with the small number of different options for creating a virtual kitchen and thus deploring a lack of reality. On the other hand, SL residents might not even want complete realism in a virtual world since to a certain degree entering into a virtual world is the result of the desire to escape RL. The most likely option is to offer very realistic virtually mass customized products (which can be ordered and consecutively delivered in RL) with additional special features for the virtual world. However, before such conclusions can be drawn, further research is needed.

In order to overcome these limitations, one first has to do exactly what Philips does at the moment, that is try to understand the consumer. But not only does an understanding of the resident within SL have to be developed, but also an understanding of the SL resident as a consumer in the RL economy. Philips decided to make the analysis of consumer behavior on SL an absolute priority. This leads to the drawback of virtual co-design "only" being of lower importance for Philips at the moment. The desire to understand the SL residents differentiates Philips' reason from Dell's reason for entering a virtual world. According to Laura Thomas, Dell's initial motivation for entering SL was the wish to be at the forefront of a new technology and to use the virtual world as a platform to explore the possibilities offered by a three-dimensional version of the World Wide Web. The lack of consumer understanding might have been the reason for Dell's virtual MC experience failure. Also Sears may solve its dilemma of too much *versus* too little reality for the virtual world through better customer knowledge. By entering virtual worlds, companies are combining fantasy and non-fantasy aspects into one commerce model. Understanding the consumer will help companies in dealing with the fact that their customers potentially move between a virtual world and the real world and how to integrate both aspects into one very realistic and real commerce model. Slava Kozlov, Senior Research Consultant with Philips Design, points out that "resident feedback suggests that it should be interactive, educational and fun rather than unimaginative with no experience exchange, or simply advertising" (Bal 2007). This was further underlined by "One of the most sticking insights working with Philips Design Friends was that even though SL is sometimes considered a virtual game, in fact it is a very serious extension of people's lives. People spend many hours online and invest energy, time, money, and even passion into it" (Bal 2007). Kaplan and Haenlein (2009a) came to the same conclusions: their results showed that there are basically four key motivations for spending time in a virtual world. These motivations are the desire to build personal, interactive relationships, the need to learn, the search for diversion and fun, and the wish to earn money. Furthermore, respondents highlighted that SL is not just a mere computer game but an extension of their RL – and that they expect companies to understand that and to take them and their SL activities seriously (for more information about how to satisfy SL residents the reader is referred to Kaplan and Haenlein's (2009c) five Cs[5] of success in virtual social worlds).

Besides these three examples of companies entering a virtual world and making use of its technology within the world, one should not forget the potential of applying 3D virtual world technology outside the virtual sphere. As discussed earlier, the fashion and automotive industries already use 3D technology independently of any virtual world. Shinsegae, the South-Korean department store franchise, uses 3D technology in the form of personalised virtual mannequins in order to help its customers in deciding what clothes to buy. Siemens together with Volkswagen demonstrated the potential of such technology in the mass customizing of cars. Also there might be opportunities for the companies Dell, Philips, and Sears to use this approach outside a virtual world. Future research has to show what different roles 3D virtual worlds/technology can and should play within a virtual world such as SL, on a corporate e-commerce site or even in the companies' RL stores.

16.4 Conclusion: Virtual Kills the Internet Star?

In 1979 the British New Wave group The Buggles released a song titled "Video killed the radio star" telling the story of a famous radio singer whose career is cut short by the increasing importance of television. This song reflects a major change in the media landscape at that time – the addition of visuals to audio signals. In the very same spirit, virtual social worlds could add another dimension to the Internet as we know it today that will probably change the World Wide Web we are all so familiar with these days. In May 2008, Gartner, Inc. estimated that by 2012 around 70% of organizations will have established their own private virtual world by furthermore stating that "Nine out of ten business forays into virtual worlds fail

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[5] The five Cs by Kaplan and Haenlein (2009c) postulate that a company should do five things in Second Life: catch traffic on the corporate island to avoid desertedness, compensate the presence of avatars on the corporate island, consider innovativeness to offer an exciting experience to avatars, create a learning environment for avatars eager to learn, and care about avatars and take them seriously.

within 18 months but their impact on organisations could be as big as that of the Internet" (Stevens and Pettey 2008). One potential change may be the higher immersiveness of a three-dimensional World Wide Web that could even be increased through the wearing of helmets or the use of other devices. Philips, for example, developed the technology amBX that enables content providers of games, movies but also virtual worlds to create immersive experiences that are felt in the real world through specific amBX devices such as lighting, airflow, rumbles, and potentially heat and water atomisers (currently prototyped). Another possible change created through virtual worlds concerns the shopping experience. While retailers in RL more and more successfully combine commerce with a social component (*e.g.*, IKEA evolved from simply buying furniture in a store into an excursion for the whole family and friends, *etc.*), e-commerce until now has been rather a very individualistic activity. Virtual social worlds might change this since it would be possible to, for example, go shopping together with other avatars in a virtual mall. Finally, it has long been shown that human beings are more efficient in processing and navigating three-dimensional spaces than two-dimensional representations. So why limit yourself to a traditional web page if you can maintain a virtual island within a three-dimensional virtual world?

Concerning MC in virtual worlds we saw that many corporations such as Dell, Philips, and Sears have tried out different strategies to integrate the customer in the production process. While Dell decided to sell real versions of their computers that were virtually customized by avatars, Philips followed a user participation strategy asking the avatars for virtual feedback in order to integrate their opinions in the RL products. Finally, Sears decided to transform its traditional MC, which is the customization of a kitchen, into a virtual MC experience. In all three cases similar patterns were experienced: both companies as well as SL residents were excited about the opportunities of virtual worlds in general and virtual MC/co-design in particular. However, all three companies encountered drawbacks and limitations. Dell ended its one-year trial of virtual MC due to a lack of profitability. Philips' priority is not yet co-design and co-creation but rather to understand the SL resident. Sears must ascertain whether their offering on SL has too much or not enough reality for a virtual world but is certain that its current form of virtual presence will not do the job in the long run.

Concluding this book chapter, five general suggestions concerning virtual MC can be given to companies already present in or planning to enter the virtual environment:

1. Understanding your customer in virtual worlds is a necessity. One major question should deal with the avatar's desired balance between reality and fantasy offered by a RL brand on its virtual world presence. This understanding must not be limited to an avatar within a virtual world but an understanding of the avatar (and RL persona behind) as a consumer in the RL economy must also be developed.
2. Do not expect too much of virtual MC. To a certain extent, user integration and virtual MC already work – however they are far from functioning perfectly and there are several obstacles to overcome in the future.

3. To sell RL MC products *via* virtual worlds does not have a satisfying profit potential yet. This is due to both virtual worlds not offering satisfying conditions (*e.g.*, no currency stability guaranteed) and avatars not being ready yet (most likely because of trust issues and security concerns).
4. Be aware of the (future) potential of MC on virtual worlds. Although several obstacles will have to be overcome in the future, there seems to be business potential for virtual MC. Companies and avatars alike are optimistic and excited about this new possibility.
5. Besides virtual MC within virtual worlds, do not forget the potential of virtual MC outside virtual worlds. Virtual environments offer new opportunities for MC activities. There might be different roles for virtual MC within a virtual world, on a corporate e-commerce site or in a RL store.

In any case, whatever importance a company gives to virtual social worlds in general and the opportunity of virtual MC in particular, it is certainly a wise strategy to prepare for the increasing importance of such applications and to build sufficient expertise in an organization today to be ready for tomorrow. If not, the same issues that the newspaper industry is facing today, due to lack of preparation for the upcoming importance of the Internet, which has resulted in a devastating decline in the number of readers and in advertising revenue for several years in a row, may have to be faced. According to author Philip Meyer, the ubiquitous availability of news on the World Wide Web, will lead, in about 30 years time (around 2040), to this industry's disappearance from the landscape. Besides, MC could be an option also in this case (Schoder *et al.* 2006), since according to Pine *et al.* (1995) products that are purchased frequently and reveal a discernible pattern of personal interest are ideally suited to being mass customized. Virtual social worlds, in the worst case, are just another form of media that companies can use in the short term to reach a segment of highly creative and technologically advanced users. But they may also be the start of a whole new era of MC, retailing, and way of dealing with customers.

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Chapter 17

Contrasting Opportunities for Mass Customisation in Food Manufacture and Food Processes

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Abstract In this chapter the concept of mass customisation is studied and the feasibility of its application to food production is discussed. Mass customisation is a concept that offers, at relatively low prices, products tailored to the requirements of the particular customer. It has increasingly become important as markets become fragmented and customers become fastidious. However, mass customisation

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is rarely applied in the food industry. This chapter investigates *via* previous literature and case studies justifications for this and presents some opportunities for the food and drink industry to exploit.

Abbreviations

CRM	Customer relationship management
DFC	Design for changeover
DFF	Design for flexibility
JIT	Just in time
MC	Mass customisation
POSIFOOD™	Point of Sale Individualized Foods
UK	United Kingdom
UV	Under ultraviolet
VFFS	Vertical form fill and seal machines

17.1 Introduction

Although many cases can be found across the full spectrum of industries, it seems that mass customisation (MC) is not widely adopted by companies that operate in the food and drink manufacturing industry. This in the UK represents 7,051 enterprises with a combined annual turnover of £72.6 billion, equating to 14% of UK manufacturing (Annual Business Inquiry 2008). The lack of MC uptake seems strange as, due to the nature of the base products in food manufacturing (predominately grains, meat and dairy), the food processing industry has to maintain a high number of product variations, making more product changes than any other of the mass-producing industries (Fisher *et al.* 2005). Many of these changes arise over short or seasonal periods, whereas some products can be stable over long periods. The need for greater customisation in food has been noted by Boland (2006) and German *et al.* (2004), who considered the potential of personal food customisation for health benefits. Furthermore, Morehouse and Bowersox (1995) predicted that by 2010 more than 50% of all inventories in food chains would be stored in semi-finished state to be finally processed and shipped on customers' demand. At present however, it looks as if this prediction may not become true.

This chapter presents the results of recent research investigating the extent of product variation and MC in the food industry. In particular, it explores the utility of specific concepts or techniques, namely: *manufacturing flexibility*, *modularity* and *postponement*. As of today, comparatively little MC research has been focused on the food industry. To understand the specific characteristics of food products, case studies have been undertaken with various food stuffs and their related product processes, of which three are presented in this chapter. This study is drawn from research that involved more than 20 UK food industry partners with different company sizes and product offers.

17.2 Research Background

This section presents an overview of events that may lead industries including food manufacturing to offer customer-individualised products. The concept of "destandardised" products on a mass basis was first mentioned by Toffler (1980). Davis (1987) coined the term mass customisation to name a strategy that offers variety and individualisation of products so that customers are able to satisfy their needs or wants without trading-off cost, quality or delivery time. The need for MC has become increasingly evident as the limitations of traditional high volume manufacturing become exposed (Eastwood 1996). With new manufacturing and wider operational practices being identified, there has been a stark awakening to the inadequacies of the traditional mass-manufacturing paradigm (Schonberger 1986). In an era of global competition, issues of product differentiation and responsive delivery quickly rose in importance (Kotha 1995). Increased product choice was introduced and customer expectations were significantly and permanently altered. Jones and Kouyoumdjiam (1993) showed that there had arisen a "fundamental shift" in consumer behaviour. Shimokawa (1994) noted that traditional product development methods and highly inflexible process-led volume manufacturing systems were unable to deliver adequate performance in these new competitive terms.

MC represents the adoption of selected refined work practices within revised business structures, leading to a highly adaptable, customer-centric, value creating enterprise (Tseng and Piller 2003). Techniques such as *just-in-time manufacturing* (Taiichi 1986), *agile manufacturing* (Duguay *et al.* 1997), *lean manufacturing* (Womack *et al.* 1990) and *reconfigurable manufacturing* (Mehrabi *et al.* 2000) are adopted, alongside other new techniques which are generally regarded as being specific to the MC model. Such techniques have been labeled MC "enablers" by recent research (da Silveira *et al.* 2001) and their implementation must be tailored to the specific market and business circumstances of the company seeking MC capability (Eastwood 1996). Also, for MC to be successful, changed working practices are required across all of business operations, from supply chain logistics through up-to-the-minute market understanding and feedback (Broekhuizen and Alsem 2002). This has led researchers to investigate the specific application of MC techniques to modern industries. For example, Wang and Liu (2009) built and analysed a multi-objective postponement model, which they applied to the notebook computer industry.

MC success thus depends on how customers perceive its additional costs and benefits (Tseng and Jioa 2001). More contemporary research has investigated the methods for including customer choice in the process (Fogliatto and da Siliveira

2008, Boland 2008), and specific design frameworks to facilitate decision making in developing customised products (Jiao *et al.* 2007, Duray 2002).

MC is typically carried out in large scale production to reduce variety costs. Although not extensively adopting MC, food processing of cakes, puddings and biscuits would benefit with this approach. An early study by Kotha (1995) researched MC implementation by a Japanese bicycle company and identified conditions required for its success. Research by Alptekinoglu and Corbett (2004) included other companies that have successfully implemented MC: Land's End (clothing retailer), TaylorMade (golf club manufacturer), Procter and Gamble (beauty care products) and Ultra-Pac (plastic packaging). MC capabilities have several other benefits, in addition to matching customer needs more closely. For instance, customisation typically eliminates finished goods inventories and their associated costs. It can also be an accurate tool for learning customer preferences, and this was also shown in the National Bicycle case study by Kotha (1995).

Further investigation on the products in Alptekinoglu and Corbett (2004) shows that MC is either derived from different configurations of packaging (shape and contents) or from product assembly. For example, Proctor and Gamble have a standard range of beauty products; these are either sold in containers of different sizes or shapes, or in a variety of "beauty packs", which consist of multiple heath care products supplied in a box or basket. Taylormade has a range of golf club heads assembled in different configurations varying the shaft material type (steel or graphic, in different flexibilities), shaft length and grips, and supplied in different patterns, colours and diameters. The National Bicycle example is similar: a generic set of parts that can be assembled to suit a rider or range of riders. In the automobile industry the same convention applies. In general, foodstuffs construction and manufacture differs from the products noted above, a fact that has been alluded to in Fisher *et al.*, (2005) and Matthews *et al.*, (2008a).

When considering MC and the food industry the published literature is sparse and disparate in nature. From a food product perspective, a discussion on the development, production and distribution of food stuffs personalised to deliver specific health benefits to consumers has been presented in German *et al.* (2004) and Kok *et al.* (2007). The authors also identified the reasons for food personalisation, specifically: consumer differences and preferences, knowledge about metabolism and food technologies. A direct link between personalised food products and MC was presented in Boland (2006, 2008), where the POSIFOOD™ system (Point of Sale Individualized Foods) is also presented. This is a system based on the concept of MC, with the customers being involved in the product design, product and sensory performance. It has been commercially developed by Fonterra Co-Op group in New Zealand and patented by Boland *et al.* (2005). From the process perspective, the authors of this chapter have presented design-led research related to the tools and approaches to accommodate product variations accompanied by MC. These can be seen in Matthews *et al.* (2008a) considering generic design rules for food processing equipment and product variation, in Matthews *et al.* (2008b, 2009) presenting specific design methodologies for MC with examples from packaging and transfer systems, and in McIntosh *et al.* (2009) considering design for changeover (DFC) and design for flexibility (DFF) for food manufacturers. Work by van Hoek (1999) investigated postponement employed in food packaging, and Twede *et al.* (2000) presented similar ideas.

17.3 Contemporary Goals for a Manufacturing Organisation

In the past, manufacturing systems were designed to produce a limited range of products. A well-known example is Ford's single-specification Model T, to which whole factories were exclusively dedicated (Abernathy 1978). For this research it should be noted that many food processing sites similarly have dedicated factories, two examples being for production of gravy/stock cubes (OXO™) and dry powered soups (Campbells). Reasons for this can be readily identified. Product cost and product quality are both perceived to benefit from high volume production, due to factors such as rigid task demarcation and precision-made components to be incorporated into larger assemblies without the need for any skilled adaptation (Womack *et al.* 1990). Other potential benefit of limited product ranges it averting difficulties with an entirely new product innovation and development. Because of these benefits, significant changes in historic mindsets and practices are required for a successful MC enterprise to emerge from a paradigm of mass manufacturing. The key driver for manufacturing system revision is the acknowledgement of a far wider and deeper customer influence on internal factory operations, *i.e.*, instigating responsiveness to highly individualised customer demands (Tseng and Piller 2003). In achieving this, the manufacturing organisation must negotiate and manage cross domain interactions and customer relationships.

17.3.1 Management of Cross-domain Interaction

The mechanisms by which relationships both within an organisation and with external partners are conducted depend on the manufacturing paradigm the organisation adopts (Pine 1993, Womack *et al.* 1990). The driving influence on the organisation also differs with the paradigm, being for example either manufacturing process-focused or highly customer-focused. Thus, exactly how an MC company is able to benefit from a primary focus on customers depends on how customer demand information propagates through the company. Optimally, this needs to occur both swiftly and in detail. Moreover, customer demand information should be used to positively influence product and manufacturing system design, for example in determining the level of response, cost and differentiation required.

17.3.2 Management of Customer Relationships

Customer information sourcing and management is an important driver of manufacturing MC; it aids manufacturing decisions (Liu and Young 2007) and “pulls” the manufacturing activity to design and make MC-compatible products. The point is a simple one: correct market information has to be available to manufacturing design and operations. The process of gathering correct market information has received considerable attention in the literature (Gentle 2002, Dyché 2001). Customer relationship management (CRM) aims to build customer loyalty through relationship-building strategies such as partnerships, branding, and good customer service; it helps companies to reinvent how they market to and interact with customers (Bligh and Douglas 2004). Furthermore, CRM provides mechanisms to define the right products to the customer (Mello 2002).

CRM generally refers to a software-based approach to handling customer relationships, and most CRM software vendors stress that a successful CRM effort requires a holistic approach (Malthouse and Bobby 2005). CRM is seen as an essential building block for the customer centric enterprise, providing information about customer response. Customers define what is required from the company, *e.g.*, product features, cost and delivery standards; it is incumbent on the manufacturing organisation to structure appropriate responses (Bligh and Douglas 2004). The better the response capability, assuming there is no penalty to the organisation, the greater the potential competitive strength. The MC organisation’s goal is clear: to provide goods and services that are customised and assembled on demand for each individual customer. Its ultimate goal is to meet individual customer’s requirements exactly without a significant increase in production or distribution cost (MacCarthy *et al.* 2003). These goals are necessarily integrated within CRM strategies. Equally they need to be integrated within manufacturing system design and operation and also product design and development.

17.4 Prominent Techniques of Mass Customisation

MC may be associated with three main strategies: manufacturing flexibility, modularisation and postponement.

17.4.1 Manufacturing Flexibility

Shi and Daniels (2003) defined flexibility in a manufacturing context as the ability to hedge against uncertainty due to complexities generated by technological advances. When considering the manufacturing system for MC, the main concern is *process flexibility* (Matthews *et al.* 2006), which is predominately a design-led activity. Williams (1994) suggested that process flexibility can be divided into two main streams: short term and long term (usually referred as re-configurability). Short term flexibility refers to the ability of a manufacturing system to process a number of different parts from a pre-defined set. Re-configurability represents the ability of a manufacturing system to process a group of parts other than those for which it was designed, or which involve significant product changeover (McIntosh *et al.* 2009).

Several strategies can be adopted by the company to foster flexibility in both manufacturing and management aspects. The manufacturing system needs to be flexible and able to anticipate a wide range of options. However, due to the vast differences in customer preferences, MC too can produce unnecessary cost and complexity. Thus, its implementation requires other supporting approaches. *Changeover improvement* is a key tool to enact responsiveness in time-based manufacturing (Mileham *et al.* 1999). Another potentially important technique is *jigless manufacture* (Whitney 2004). There has also been research into product and process design to cope with the effects of MC implementation. For example, Tolio and Valente (2007) considered a stochastic approach for machining operation systems to manufacture part families. Matthews *et al.* (2006) employed a constraint-based technique to assess the ability of production equipment to manufacture variants products. Another technique to induce manufacturing flexibility into a production environment is that of reconfigurability. Examples of reconfigurable systems are presented in Mehrabi *et al.* (2000) and Mullineux *et al.* (2009). Fisher *et al.* (2005) present the concept of modelling food products for late customisation. Seepersad *et al.* (2005) concentrated on *planning of product families* and *platform development*. These approaches aim at producing variety efficiently and effectively, with the main emphasis being on financial benefits.

Besides these works, some wider discussion of food industry supply chains, marketing and customer relationships have been published (Dole 1999). The lack of food industry uptake may be due to the fact that the MC paradigm is still maturing, or because of the differences between food manufacturing and other industries.

17.4.2 Modularity

Modularity is a well known technique in product design. It refers to the division of products into sub-assemblies and components so that more variety of products can be offered. Modularity allows calibration of the level of customisation for the entire product with respect to each feature/function (Kumar 2004). It was adopted, for example, by Densai and is described by Whitney (2004) as the "combinatoric method of achieving model-mix production". Secondly, the literature often cites a *decoupling point* (Winkner and Rudberg 2005), representing the point at which a company's activities switch from speculation to commitment. The better the understanding of customer demands, the lower the degree of speculation it has to endure. Modularity can not only improve not only product variety but also delivery time and scope economies (Duray 2002).

17.4.3 Postponement

A very similar technique is *delayed differentiation* (Aviv and Federgruen 2001). It means leaving the product differentiating activity as late in the manufacturing process as possible. It is a tactic that enables pseudo-responsiveness of the manufacturing system in the eyes of the customer by relying on responsiveness only of later manufacturing operations. In truly responsive organisations, where response capability is present throughout delayed differentiation is unnecessary. Delayed differentiation is another term for the much more usually applied term of *postponement* (van Hoek 2001), meaning postponement of the product differentiating activity. Postponement allows companies to reduce their inventories of finished products so that the cost of storing them in the warehouse can be saved. At the same time, the risk of making excessive products by misjudgment of future demand can be reduced. In this way, companies are able to manage the uncertainty of market demands which is changing rapidly from day to day.

The concept of postponement has been further divided into four generic types:

1. *Form postponement:* involves delaying certain activities of the manufacturing process until the customer places their order. It is not suitable for products that require short lead time because extra time is necessary for the final processing. Form postponement can be divided into four main streams (Zinn and Bowersox 1988):
   1. labelling postponement;
   2. packaging postponement;
   3. assembly postponement; and
   4. manufacturing postponement.
2. *Time postponement:* refers to delaying the transit of products until the customer's order is received.
3. *Place postponement:* means the positioning of inventories upstream to postpone the forward or downstream movement of products.
4. *Logistic postponement:* refers to a combination of time and place postponement and can be applied to the structure in which goods are stored at a limited number of centralised locations and products are dispatched after the customer orders are received.

17.5 Case Study Investigations

The following section presents three of the case studies investigated during this research: yoghurt, batter base puddings and potato crisp production, and analyses their potential for the application of MC. Products are depicted in Figure 17.1.

The three manufacturing companies are deemed as employing modern manufacturing practices. Continuous improvement was actively demonstrated in all sites. The companies have strong individual brands in the UK, and the potato crisp

Figure 17.1 The products: (a) yoghurt, (b) puddings, (c) potato crisp

manufacture and batter puddings produce for supermarket home brands as well. They all show good customer relationship management practices.

17.5.1 Case Study Processes

In general, yoghurt is made with a variety of ingredients including milk, sugars, stabilisers, fruits and flavours and a bacterial culture. During fermentation, these organisms interact with the milk and convert it into a curd. They also change the flavour of the milk giving it the characteristic yoghurt flavour. To modify certain properties of the yoghurt, various ingredients may be added: sucrose for sweetening and cream for a smoother texture. The consistency and shelf stability of the yoghurt can be improved by the inclusion of stabilisers such as food starch, gelatine and pectin (Tamime and Robinson 1999). These materials are used because they do not have a significant impact on the final flavour. The use of stabilisers is not required, and some companies choose not to use them in order to retain a more natural image for their product. To improve taste and provide a variety of flavours, many kinds of fruits are added to the yoghurt. Figure 17.2a, shows the process steps in industrial yoghurt production.

Mass marketed potato crisps became popular in the late Victorian times. The introduction of air tight bag in the 1920s to keep the potato crisps fresh enhanced the product's popularity. The mass production of crisps is a continuous process. Raw product is brought to the factory. Potatoes are washed, peeled, sliced and deep fried. Post frying, the flavours are added and then the product is packed in bags. The packaging and sealing of the potato crisp bags are crucial to the longer shelf life. The process steps for crisp production are shown in Figure 17.2b. The third process is that for frozen batter based puddings (*cf.* Figure 17.2c). Batter is a liquid mixture, usually based on two flours combined with water, milk and eggs. The raw products are supplied to the factory. Both flour and eggs are in powder format. These are sieved prior to mixing. The final product is supplied in two forms: frozen batter in tray for home cooking and precooked puddings for reheating. Additional herbs and seasonings are added to individual customer's requirements. The primary packaging of the frozen pudding is an overwrapped polypropylene bag and then a carton for secondary packaging.

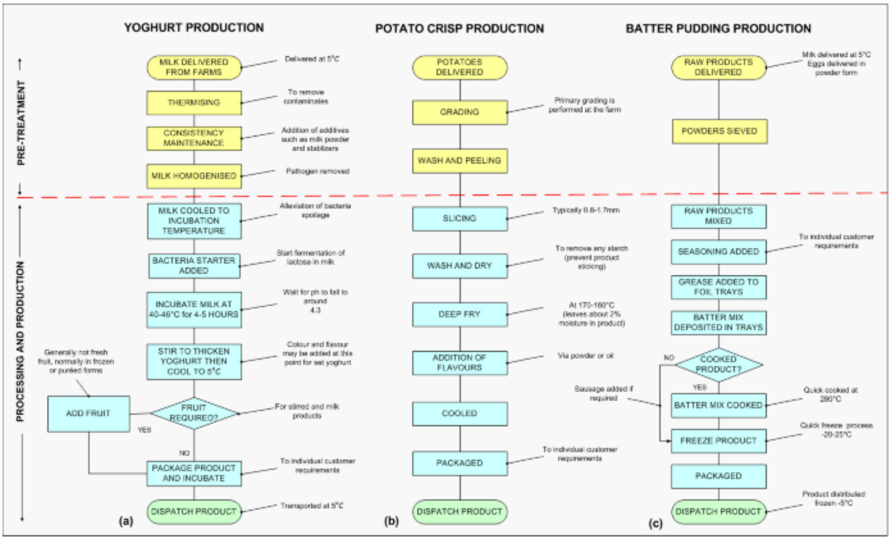

Figure 17.2 Flowcharts of case study processes

Table 17.1 Degrees of variation of case study products

	Yoghurt	Potato crisp	Batter pudding
Variations in product	Consistency: Drinking Stirred Set	Thickness: Profile Plain Rippled	Physical: Frozen Cooked
	Flavouring: Natural Fruits Synthetic	Flavouring: On product In sachet	Size: Small Large X-large Giant
	Fats: Low Medium Full	Flavouring mode: Oil-based Powder-based Packing Bag size Multipack	Mix: % of milk to water Beer Seasoning Organic mix Additives Sausage
	Additives: Enzymes Vitamins		
	Packaging: Carton Tube Bottle Multipacks		Packaging: Profile of foil tray Size of bag Multipacks

The cooked product is supplied in a polyethylene bag format. The production processes of yoghurt, potato crisps and batter puddings are similar, as they all have pre-processing stages and the main production process is continuous flow. They differ from other "mechanical products", which are generally manufactured in processes comprised of discrete process steps. The current levels of variation for these products are shown in Table 17.1. It must be stated that these products are mass produced. The production lines are set up and the thousands of individual products are produced. The packaging materials are ordered well in advance of the start of production.

17.5.2 Potential for the Application of Mass Customisation

The potential for application of the MC strategies in the three production setups has been analysed and the results are summarised in Table 17.2.

Manufacturing flexibility: a common factor to case studies and to the other companies investigated during this research was that flexibility in the manufacturing system was not considered. All companies bought dedicated manufacturing systems to produce their specific products. As noted in previous research (Matthews *et al.* 2006), the designed system have an innate capability to handle slight variations in product, slightly thicker consistencies, larger potatoes, changes in the material properties of the packaging, maybe caused by the environment (mois-

Table 17.2 MC applicability to case studies (adapted from McIntosh *et al.* 2009)

	Yoghurt processing		Batter based puddings		Potato crisp production	
Modularisation	P	It is possible to make a standard base for all yoghurt products including yoghurt with and without fruits, yoghurt drinks and other products	P	It is possible to make the base mixture for all pudding products	Y	Broadly, it can be said that it has already been applied, because uniform crisps are made and then flavoured. This can be regarded as modularisation. However it is only possible to differentiate the flavour but not the thickness or texture
Manufacturing postpone ment	N	Because the yoghurt production is a flow from the arrival of the milk, it is not sensible to stop the flow in the middle of production stage	N	As with yoghurt the production is a flow, it is not sensible to stop the flow in the middle of production stage	P	If it is possible to store the sliced potatoes by freezing, normal and lighter (lower fat) crisps can be offered. However, considering shorter life of slices compared to deep fried crisps, it is very unlikely

Table 17.2 Continued

	Yoghurt processing		Batter based puddings		Potato crisp production	
Assembly postponement	P	Linking with modularisation, it is possible to delay the addition or altering of yoghurt, however there is very little time available to do this (maximum few days). Consequently the shelf life of the yoghurt reduces	P	As with yoghurt, linking with modularisation, it is possible to delay the addition or altering of the product, however there is very little time available to do this (maximum few days)	P	The customisation of the flavouring and additives can be customised according to the customer order; it may have been applied already. However, this assumes that flavour does not need to be added right after deep frying and also not required to be packed as soon as possible
Labelling postponement	P	This option is dependent on the location of the factory, if it is UK, probably not. Because it is not sensible to ship the yoghurt over long distances. However the regulation for recipient county needs to be considered	P	The packaging has been already printed before pudding is packed and it may be hard to label on the already packed pudding. Some packing films offer the potential for printing in the packaging process	P	As with the pudding example, the packaging has been already printed before the product is packed and it may be hard to label on the already packed crisps. Some packing films offer the potential for printing in the packaging process
Place postponement	N	As with time postponement, it is not sensible to store the finished yoghurt until the customer order	N	As with time postponement, it is not sensible to store the finished product until the customer order	N	As with time postponement, because of its relatively long shelf life, it is possible

LEGEND: Y = MC technique applicable, P = possibility for MC technique, N = no potential for MC technique

ture), *etc*. This is initially achieved by simply providing user adjustments or complete sets of change parts. By the appropriate use of these approaches most normal variations in product setting can be handled. However, when major changes in product size and configuration are required there is no guarantee that the existing machines will be able to provide the desired response. This is a key limitation if such companies are looking to change configuration of the products.

1. *Modularisation:* for yoghurt this may be possible. Investment in additional equipment which enables the variation of the yoghurt products as well as information technologies to provide very prompt response to the retailers' order is required. Since that would increase the distribution cost, it is unlikely to be adopted. Modularisation of the potato crisps and puddings is already applied in a way, since the standard crisps and batter mixes can be viewed as the module, which is customised by addition of desirable flavours and additives.

2. *Packaging postponement:* for the three products packaging can be postponed until the customer orders are received. The choice includes a big carton, small carton or multiple packs. The only disadvantage of this is that the time is limited and shelf life can be reduced.
3. *Labelling postponement:* this has potential applicability in all products. Within Europe, the yoghurt cartons can potentially be printed in the required language and dispatched. This, however, also has the potential to reduce the shelf life of the yoghurt at the retailer. On the other hand, the carton of the yoghurt can be modularised, by being printed in the several languages. The yoghurt also needs to be qualified for all the regulations that might apply. For the potato crisps and the puddings there is the potential to label or print the packaging films prior to bag construction and sealing.
4. *Time postponement and place postponement:* this may already have been applied. However it needs to be clarified who is responsible for the inventory costs at the retailer. If the costs are to be covered by the manufactures, then it is ideal to carry out the logistical postponement (combining and time postponement and place postponement). If, however, the retailer is responsible (probably the most likely) then, it is actually better for the manufacturers to push the inventory to retailers as soon as possible, ideally right after the product is manufactured, eliminating inventory costs.

For these case studies it has been indicated that the dominant reason behind the lack of MC take-up is, that retailers are actually urged to maintain sufficient stocks and product availability for their customers' (shoppers), therefore certain finished goods are pushed to the retailers (shops and supermarkets). Therefore, for the manufacturers there is no need to keep the high level of inventories of their finished goods. It is however, not necessarily applicable for all the food products but this is assumed to be true only when the products have relatively long shelf life. Because inventories at the retailers can be stored for longer time and the probability that all inventories will be sold without wasting some due to perishability is more likely. On the other hand, for the shorter shelf life products such as yoghurt, it might not be realistic because yoghurt needs to be sold in relatively quickly and in shorter time, so retailers are less keen on keeping safe stocks. This might explain why in the supermarket only certain products such as vegetables, meat, fruits or dairy products (those products with short shelf life) are sometimes found sold out whereas product with long shelf life such as crisps, chocolate or canned food are always available.

17.6 Food and Drinks Manufacturing Constraints

Analysing prior literature alone, suggests that the lack of food industry uptake may be a reflection that the MC paradigm is still maturing. More critically, however, poor levels of MC uptake may be because of important differences in either food manufacturing processes or the industry's products when contrasted with more usual product industries (automobiles, vacuum cleaners and footwear). Previous research has noted the "enablers" for MC (Da Silveira *et al.* 2001); this section has identified "constraints" that are imposed by the products and processes in the food industries, which may restrict MC uptake. These "constraints" can be categorised under three headings: product, operations and systems.

17.6.1 Product Related Constraints

Investigation into the raw product that the food industry processes shows they can be categorised into five forms: liquids, pastes and slurries, particulates and solids (both rigid and soft bodied). Examples of products that fit into these categories can be seen in Table 17.3. The ways in which the products are produced potentially play a major factor in the ability of the organisations to implement MC.

Table 17.3 Food product taxonomy

	Liquid	Paste/slurry	Particulate	Rigid body solids	Soft body solids
Examples	Milk Soft drink Beverages Soups	Yoghurt Fish pastes Yellow spreads Toothpaste Jams	Coffee Sauce-granules Tea Cake mixes Pasta	Chocolate Cookies Frozen vegetables	Bread Cakes Meats Jelly

1. *Mixing/blending:* in its simplest form, purely mixing ingredients can be seen as different to assembling products. An implication is that mixable ingredients are either in finely divided or liquid form. Equally, there are no assembly precedent relationships in thorough, pure mixing, unless chemical change considerations apply. Potentially, therefore, mixing is a much more easily automated activity than conventional assembly. Although this can restrict the ability to individualise the product, changing the composition, could affect the base product, texture and/or taste. An example could be the addition of vitamins or minerals to snack bars; it can be very difficult to disguise the flavours of the additives.
2. *Chemical change:* for many food processes the products under manufacture experience chemical change as a result of being mixed or otherwise combined. Chemical change always occurs during cooking and fermentation. As with mixing and blending, this can be can restrictive and may affect the base product, texture and/or taste. An example seen in this research was a supermarket asking for the removal of sodium-based salts from bacon for a health campaign. They used potassium-based salts, which tasted slightly different to the customer, but this could also cause the product to decay more quickly (more waste); this also conflicted with the lower food waste campaign the company was running concurrently.

3. *Maturing cycles/delay:* some food products need to undergo a maturing cycle. This is the case with cheese; stilton might be expected to be stored (in carefully controlled conditions) for between 3 to 6 months prior to sale from the factory. For a few selected products, for example, whiskey, the storage period may be considerably longer. The same issues apply to this stage as with mixing/blending; changes made could affect the customers' perception (taste/texture) of the finished product.

17.6.2 Operation Related Constraints

Operation related constraints are generated as food stuffs require different processing conditions, clean rooms, *etc*., and the ways in which machinery and humans contact the product, giving rise to very stringent health and safety regimes.

1. *Distribution*: many foodstuffs have special distribution requirements. For example, fruit and vegetables need to be processed as quickly as possible once harvested or, later in the overall manufacture and distribution chain, they are certainly required to be at their retail destination as quickly as possible. This is effectively a time constraint on production. This potentially limits the ability to customise the product before distribution.
2. *Economies of scale:* for some industries, for example, steel and some chemical processing industries, economies of scale are disproportionately influential on final product cost. In these particular circumstances selected MC tactics that are reliant upon disrupting true uninterrupted high volume production may be much more difficult to apply. The same inhibitions may also apply to specific food processes where, by virtue of an economically constrained manufacturing process, techniques like late-postponement options are difficult to use.
3. *Handling:* food products are generally more delicate than many "mechanical" products. Special handling considerations may in themselves limit MC implementation. Special handling can apply both during processing and distribution (Matthews *et al.* 2008). This generates a cost constraint, changing transfer devices and manipulators, *etc*., adds addition costs to the processing equipment. An example is a manufacturer adding an additional snack bar to a pack for promotional purposes. This increases package length and weight, causing redesign of the end-effector, on the pick and place packing unit.
4. *Legal provisions (sell by date and others):* the complexity of specific legal provisions in relation to food may inhibit MC implementation, such as identified in the food safety act (Food Safety Act 1990). This limits the potential to individualise products, as one is constrained to stay with these legal provisions. Health scares are not good for any businesses' long term survival!

17.6.3 System Related Constraints

System related constraints are generally associated with equipment design. The equipment is designed to process the end product. How the system is run is not always a consideration at the design stage. Also, some equipment is generic, *e.g.*, ovens, mixers and wash units. If the company wants to customise the product, it may require additional features not offered in a generic system. It is also not uncommon in the food processing industry for equipment to be inherited or purchased second hand, so it may have been designed for a slightly different product.

1. *Accessibility:* access to the place at which value is being added to a product (where physical change is occurring) may be restricted. For example, when heat is an agent of change it is unlikely that access is easily available. Moreover, many other food industry process events occur in vessels or pipes within in flow lines; it may often be indeterminate when such events actually occur. This can severely limit the potential to individualise products at various stages of its production.
2. *Cleaning/purging:* more than for most other industries, and especially considering cross contamination (food allergies) and hygiene, food processes are liable to be subject to stringent cleaning requirements. There is no doubt that cleaning in any case represents a major problem, even in many conventional product changeovers (McIntosh *et al.* 2001). Although specialist food process cleaning techniques can be of assistance (Quarini 2002), experience in different factories manufacturing or packaging food products indicates the extent of the general cleaning problem. In previous research at a frozen vegetable packing company, effort devoted to clean down process equipment varied considerably depending on which vegetables were being switched between. Major periodic equipment cleaning was also undertaken. During product changeover at this factory clean down could represent up to 53% of *per*-changeover man-hour losses. (McIntosh *et al.* 2001). Financially, this could be very restrictive if trying to individually customise sort batches for customers.

17.7 Discussion and Opportunities

This chapter has contrasted the theory and practice of what has been termed conventional product MC with a theoretical appraisal of MC implementation in the food industry, for which much more limited research is available.

To date 23 food manufacturing companies have been visited. It was found that all have adopted “modern” manufacturing practices, irrespective of company size or staff employed. The concept of Kaizen (continuous improvement) was well known to the manufacturing staff. Many of the companies employed just-in-time manufacture; all keep very low levels of stock post and prior to manufacture. Although it must be noted that with the base product, dairy, arable and meat, there is always a need to process quickly, *e.g.*, with packed mixed baby salads leaves, the whole process cutting to packing is completed in 5 h. In relation to CRM the companies investigated had strong products brands with large customer bases. Also, many of the companies produce their products for supermarket home brands. Their CRM as equal to or even more established than that of many other industrial sectors. Aspiring to MC, and with a wide range of manufacturing process improvement techniques at hand, a decision has to be taken as to which techniques should be adopted, and whether indeed it could be adopted in food manufacturing circumstances.

This chapter identified the key constraints that differentiate food stuffs from conventional products. These are the constraints that affect the successful implementation of MC techniques to existing and potential equipment/setups. These constraints have been categorised under three headings: product, operations and systems.

1. *Product constraints:* the core differences between food stuffs and mechanical products are that mixing rather than product assembly takes place and that chemical reactions occur very frequently, which are time dependent and irreversible.
2. *Operations constraints:* food stuffs need to be processed and distributed quickly, have complex handling requirements and are produced under demanding legal requirements
3. *System constraints:* access to the place at which value is being added to a product is generally restricted, *e.g.*, ovens or piping. Also cleaning/purging the system is generally difficult. Not lending itself to multiple changes in product.

Table 17.4 Factors of non-food industry MC take-up

Factor	Description
Rationale	It is sometimes not sensible or possible to change the processes of food production (*e.g.*, addition of yeast at the end of bread production)
Consumers customisation	The food can easily be customised by consumers at home
Retailer customisation	Some of the food products can also easily customised by retailers (*e.g.*, in terms of volume of the food)
Applicability	Modularisation in general is not applicable to food
Product demand	The demand of the food is relatively stable and easier to be predicted than the other products including the seasonal fluctuations
Storage	Some food products cannot be stored for long period due to perishability
Semantics	It is already applied but not classified or identified as mass customisation
Costing	Distribution costs are more important than the inventory costs, therefore not suitable for place postponement

Many of these constraints only come into effect if small manufacturing volumes are required. It has been stated that most of these constraints could be overcome with increased manufacturing expenditure, *i.e.*, increased manufacturing flexibility possibly derived by reconfigurable system. Approaches to support this have been presented in McIntosh *et al.* (2009). This is unlikely to be due to the low profit margins in of the individual food and drink products.

Table 17.4 presents the eight factors that may explain why MC has not been fully implemented in the food industry to date. It must also be noted that many of these constraints could be overcome with increased expenditure, but as profit margins on food stuffs are low, there would be little benefit to the manufacturer.

17.7.1 Packaging and Labelling

As seen from the case studies, one opportunity to employ MC techniques is in packaging and labelling postponement. Previous research by Twede *et al.* (2000), presented that packaging postponement could increase a company's flexibility to respond to changes in the demands from different market segments, improving operational responsiveness and reducing inventory and transportation. Current work at the University of Bath is investigating such an option further and considering the effects of sustainability in the packaging market. This section briefly describes some options that are open to the food industry; these are again demonstrated with the three case studies.

Both pudding and crisps products are supplied in bagged form; bags and pouches are very common ways to package and present food stuffs. Such bags are produced on vertical form fill and seal machines (VFFS). These machines produce bags from a reel of packaging material. The packaging material is generally supplied as a reel of flat, pre-printed film. The process of forming the material is shown in Figure 17.3. The web of material is drawn from the reel through the web tensioning system, and over a forming shoulder, which guides the material from flat to a cylindrical shape around the product feed tube. The action of forming the cylinder brings the outer edges of the film together. These are overlapped so that the sides of the film meet. These are usually sealed by applying heat and pressure. The process has now created a tube into which the product is dropped in measured quantities. The tube is then cross-sealed and cut to form the complete bag (the action of making this final top seal to one bag also forms the bottom seal of the next bag). VFFS system can pack products up to 140 bags *per* minute, for a 200 mm length bag this related to 28 m of film *per* minute. Similar to this operation is that of horizontal form fill and seal (flow wrappers), this is effectively the VFFS operation leaning on its side. This is also commonly applied packaging for food stuffs, examples being secondary packaging of chocolate biscuits, and overwrapping of trayed products, pastas, meats, *etc*. Such flow wrap systems have the potential to pack products at over 600 units *per* minute.

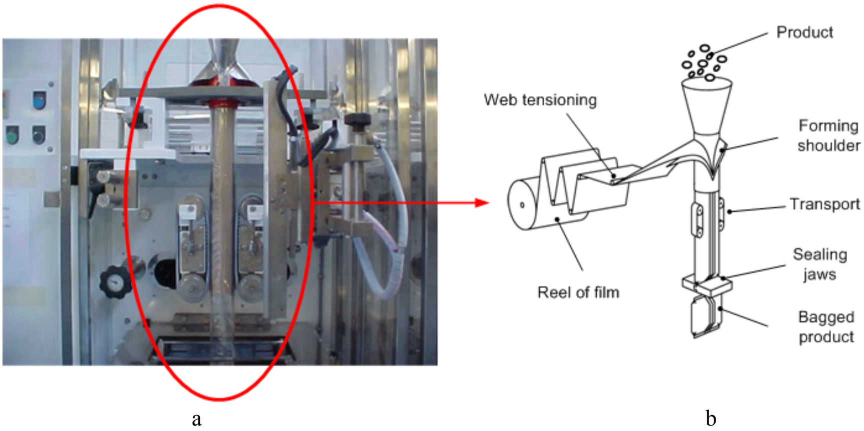

Figure 17.3 VFFS operations. Front view of VFFS machine (a) and VFSS process schematic (b)

VFFS presents two possibilities to customise products: firstly using a blank film and adding labels to the either the tube as the bag is being formed (between transport and sealing jaws), or adding an additional operation post bag and then labelling. Secondly, exploiting the potential of quick printing, as used in the commercial print industries (magazine and paper). In the printing industries, films are printed and cured at speeds of 12 m/s. For VFFS operations a customised print can be added to the film prior to conversion into bag (post web tensioning). The combination of the surface preparation and quick drying inks under ultraviolet (UV) light (Kokot 2007). The UV inks employed are actually monomers, which polymerise under a UV light source. This process easily permits printing, curing at operational speeds employed by food producers (up to 140 bags *per* minute). Printers are already incorporated on VFFS machines to add date coding. It would not add too much cost to expand such units. These options are in addition to the purchasing of the packaging media after the customer order is placed, as previously noted.

In the case of yoghurts, the printing of packing media during operation can be performed, but this becomes much more complex, as the pot/tube and foil lid may need to be printed. As with the bagged product, printers are employed in process to code the packing. Industry standards dictate that the product is printed at least 300º around the yoghurt pots. So to perform this additional stand alone equipment would be required. Labelling of the product presents similar problems. This option could be exploited for other film packaging operations. Labelling of food stuffs in this manner is expected by customers when purchasing from farm/market shops. If mass production food manufacturers are comfortable with product presentation, this is definitely an area to be exploited. If customers want "customised packaging", there are additional costs; unwillingness of companies to pay these costs may also be a reason why MC is not widely adopted in the food processing industries. This also relates to economies of scale, as noted in Section 17.5. The ideas presented in this section are the follow-on direction for research and application at the University of Bath.

17.8 Conclusions

In summary, food manufacturing companies employ modern manufacturing strategies, lean and JIT, and have comparable CRM to that of other manufacturing industries. From an operational perspective, things are in place to adopt MC. It has been proposed in this research that it is possible to implement MC to some food products through strategies such as postponement or modularisation. However, it is important to analyse each step of the manufacturing processes and all the consequences need to be listed.

Although there are manufacturing and operational constraints to be considered when implementing MC, these could all be overcome by increased expenditure and the development of more "flexible" processes. Low individual product cost may also be an additional constraint. It has also been presented that there is a need to package all food and drink products for preservation and protective purposes. This presents the simplest and greatest potential for companies to individualise products for their customers.

One final reflection concerns differentiating food preparation in a factory with what is possible in the home kitchen environment. There is the scope to prepare many foodstuffs at home, and if done well these can exceed the quality of factory alternatives (including preservation measures and distribution). Food and drink at home can always conceptually be prepared exactly to a preferred personal specification. In an ideal world an MC company could match this – although this chapter suggests how difficult this might be, typically, this goal is possible to achieve.

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