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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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 row-wise 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.

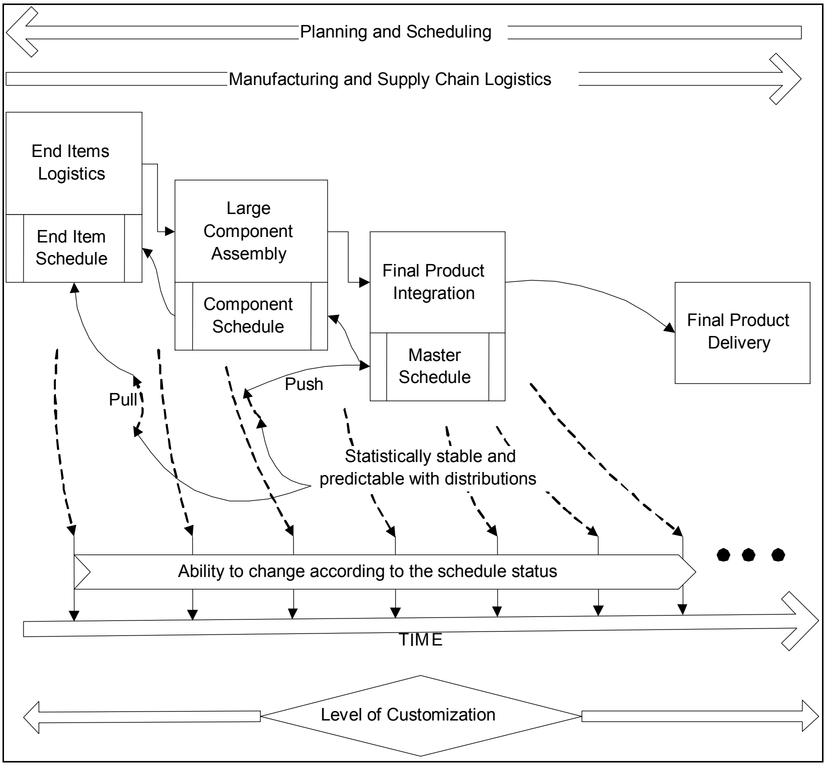

Figure 1.1 System modeling of a customized product supply chain in a large, integrated system (Lu *et al.* 2007)

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.

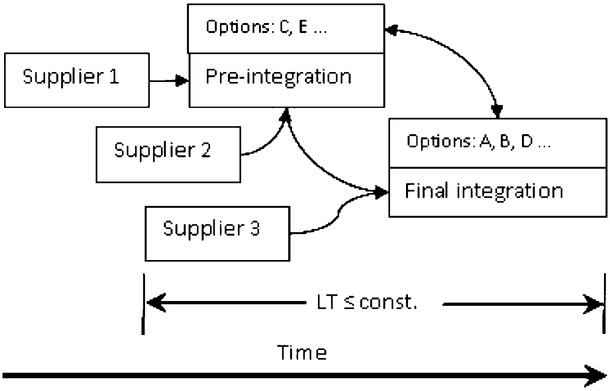

Figure 1.2 Overview of a sample system (Lu and Storch 2005)

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.

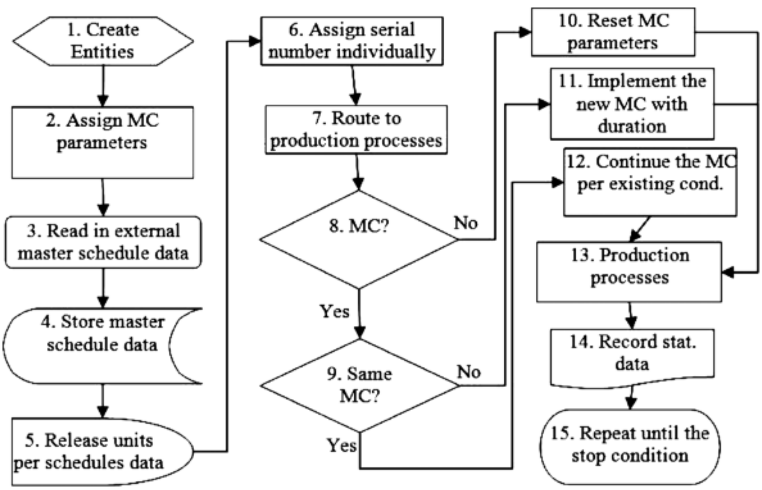

Figure 1.3 Modeling an MC system using discrete event simulation (Lu and Storch 2005)

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.

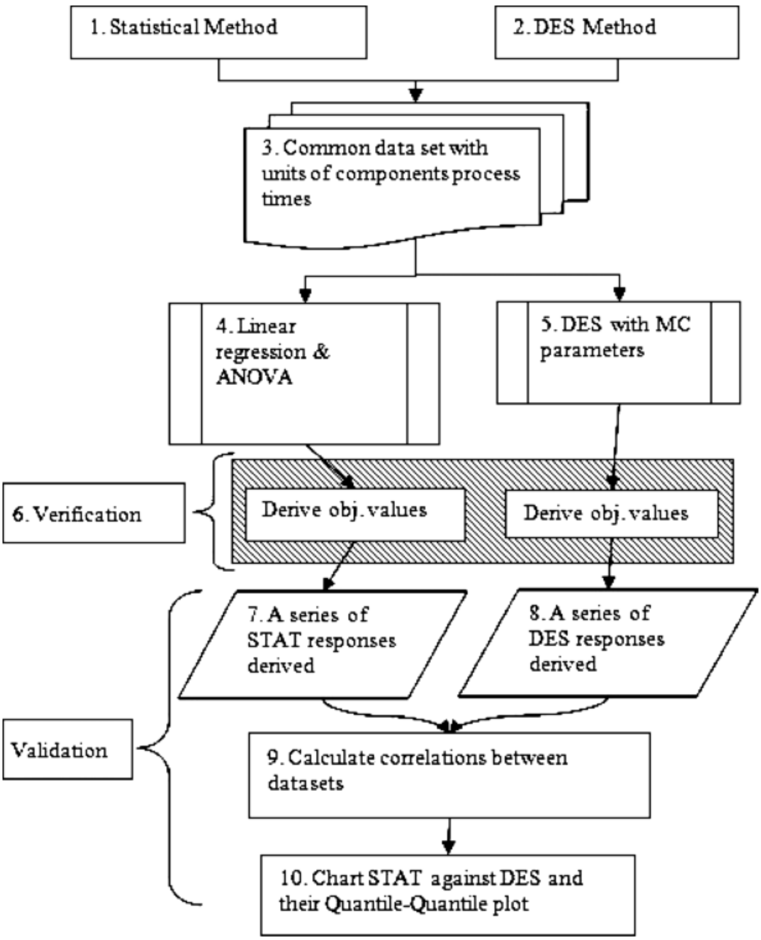

Figure 1.4 Statistical and discrete event simulation method verification and validation

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.

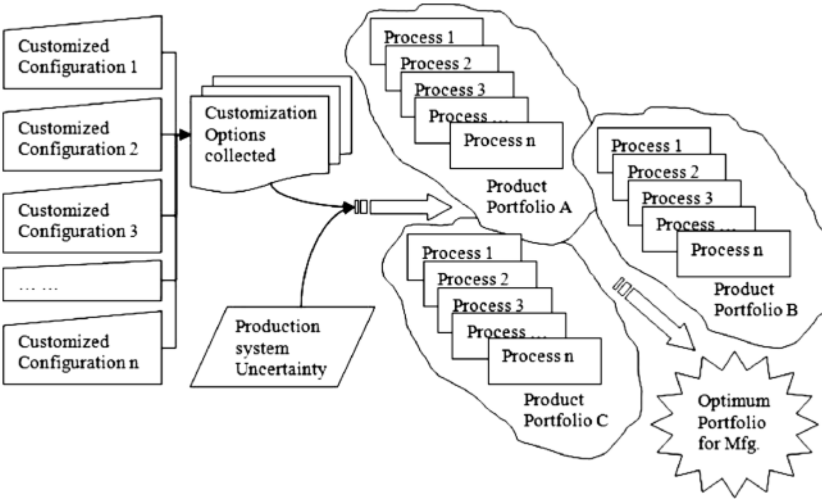

Figure 1.5 Customized configuration to optimum product portfolio for manufacturing

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.

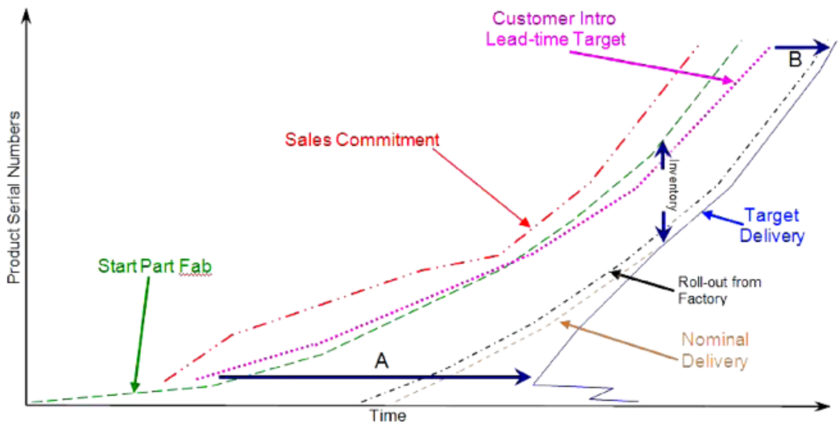

Figure 1.6 Major event relationships in a large scale production system

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.

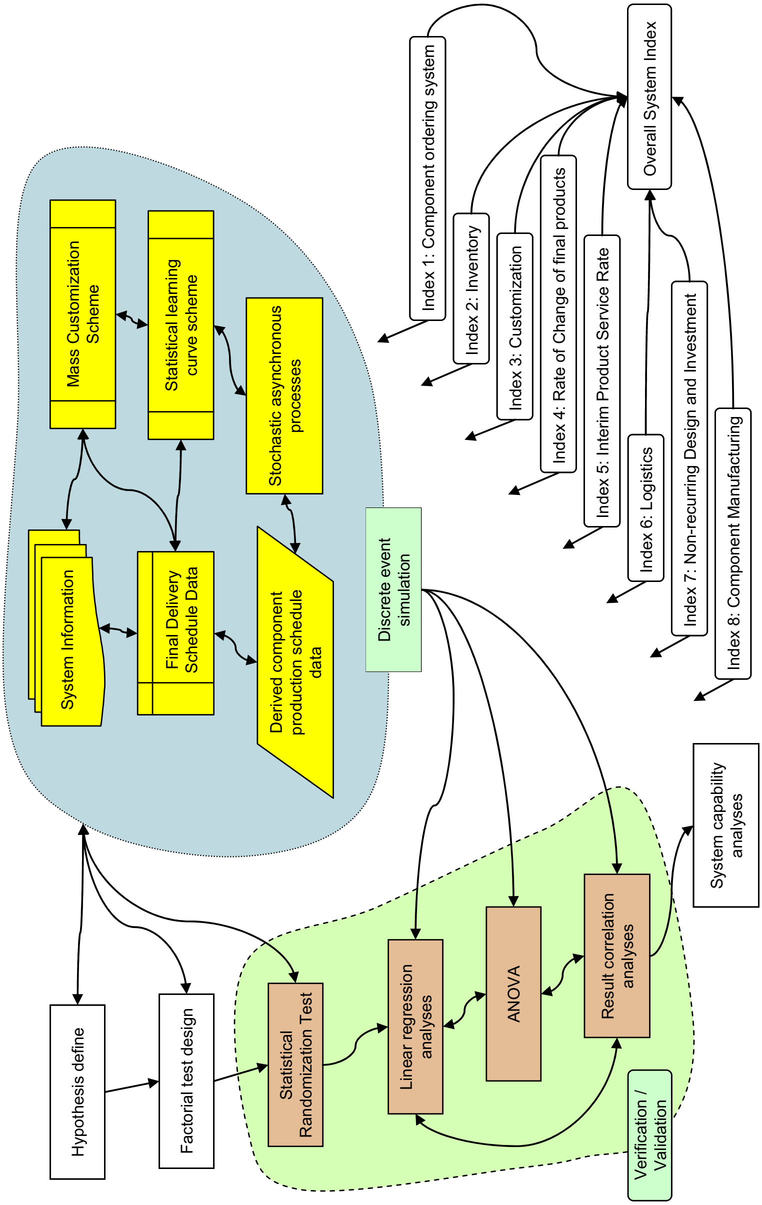

Figure 1.7 Research approach methods

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.

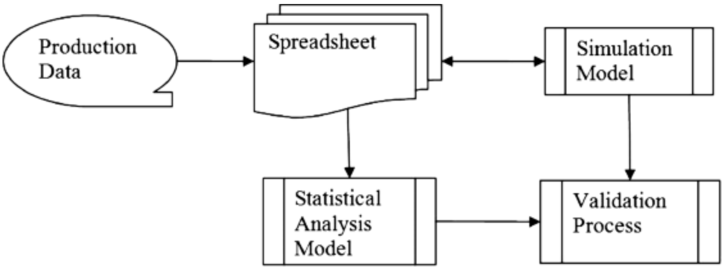

Figure 1.8 High level data structure

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.

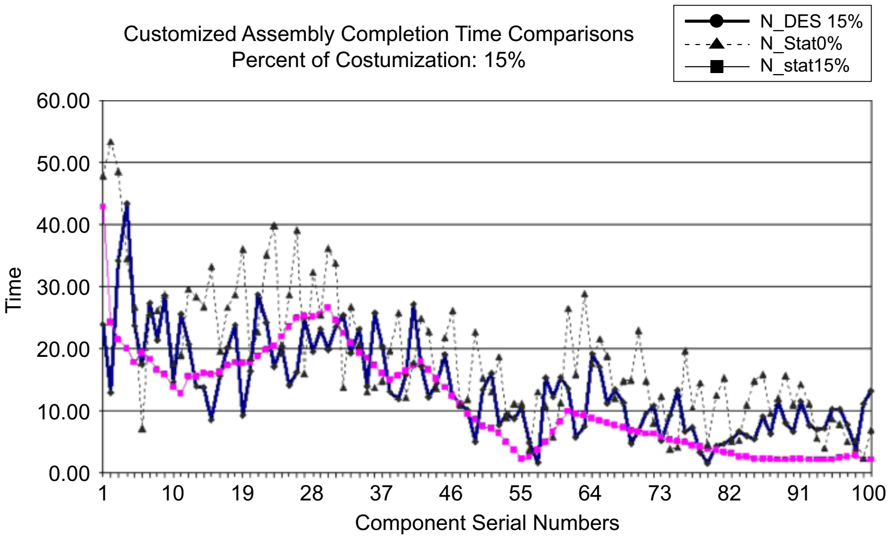

Figure 1.9 Process completion time comparison between two methods

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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