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Modeling customized product configuration in large assembly manufacturing with supply-chain considerations

Roberto F. Lu · Thomas D. Petersen · Richard L. Storch

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Abstract Dynamic variability in low-volume and highly customized products of a large assembly manufacturing system with an integrated supply chain has been very challenging to capture. Design and product configurations most likely impact outcomes of such broad variability. This article presents a framework to encompass this completely integrated system for using discrete event simulation as a modeling method. The system modeling framework addresses factors including customized configuration attributes and individual customer-preferred considerations for customized configurations. The framework is intended to aid decision-making concerning cost and schedule impacts associated with customization options chosen throughout the supply chain. A real-world example drawn from aerospace is included to demonstrate and validate the operational capability of the proposed framework.

Keywords Mass-customization · MCM · Discrete event simulation modeling · Supply chain · Aerospace · Framework

R. F. Lu (✉)
The Boeing Company, Commercial Airplanes Material and Process Technology,
Mail Code: 19-FA, PO Box 3707, Seattle, WA 98124-2207, USA
e-mail: roberto.f.lu@boeing.com

R. F. Lu · R. L. Storch
Industrial Engineering, University of Washington, Seattle, WA 98195, USA
e-mail: rlstorch@u.washington.edu

T. D. Petersen
Aalborg Industries, PO Box 844, Gasvaerksvej 24, Aalborg 9100, Denmark
e-mail: tdp@production.aau.dk

T. D. Petersen
Department of Production, Aalborg University, Fibigerstraede 16, Aalborg 9220, Denmark

1 Introduction

Customized configuration starts right from the product conception stage. The balance of customization and standardization among market demands, manufacturing capabilities, new product designs, and supply-chain logistics in integrated systems has been a continuously evolving challenge. Individually customized products have always had their market niche, both before and during the mass-production era.

Configurations can be drastically different, whether the final product will be mass-produced or mass-customized. Various product configurations can be demanded from different market segments. Considerations for customized personal products such as clothes and shoes, which can be manufactured in factories that do not require special infrastructure features, are not the same as those for large, integrated products such as ocean vessels and airplanes, which literally cannot be assembled without feasible infrastructure in place. This article focuses on large-scale assembly and integration of customized products with considerations of related supply-chain issues.

Supply chains consist of interlinked networks of suppliers, manufacturers, distributors, and customers who provide a product or service to customers (Blackhurst et al. 2004). Stochastic operations of typical supply chains can be equipped with Internet technologies on a network-based methodology to model, react, and change supply-chain systems. Supply-chain impacts from low-volume and highly customizable products require a certain level of supply-chain agility, especially the ability to reconfigure dynamically and quickly according to demand changes in the market. An architecture employing case-based reasoning can be used to analyze the management of agile, multi-agent-based supply chains (Lou et al. 2004).

A framework for simulation modeling of a transporter-constrained supply chain of customized products in an integrated manufacturing system is explored in this research.

2 Background

This research is based on mass-customization, supply-chain modeling, and simulation.

2.1 Mass-customization

Levels of product customization depend on product volume and design configurations. The more mass-produced a product is, the less the likelihood of mass-customization. It is important for design teams to explore the customer's perception of the appearance of a target product. A research effort combining virtual prototyping (VP) with design by manufacturing simulation techniques, which allowed individual customization requirements and the process capabilities of a company to be balanced in the design stage, was reported in Tseng et al. (1998). The types of VP presented in their paper include immersive virtual reality and analytical virtual reality. Key techniques using VP-aided design of customized products consist of product representation and model generation, human-computer interaction, manufacturing simulation, and product library.

A finding by Hartley et al. (2004) suggests that contrary to expectations, e-auction use and supplier collaboration are not mutually exclusive. This study shows that purchases of custom production parts and components by e-auction adopters versus non-adopters were 24 and 22%, respectively.

In an integrated manufacturing system, modular products are gaining popularity. A mathematical model introduced a modularization function for analyzing the degree of modularity in a given product architecture (Mikkola and Gassmann 2003). This article indicates that modular products may shorten new product-development time and help to introduce multiple product models quickly with new product variants at reduced costs, as well as many successive versions of the same product line with increased performance levels. This concept in levels of modularity can be similarly extended to reflect levels of customizations in both product design and supply-chain structures.

Spare parts have an intermittent or slow-moving demand pattern, presenting particular problems in forecasting and inventory control, as outlined in Eaves and Kingsman (2004) who used extensive demand and replenishment lead-time data to access the practical value of forecasting models. The paper provides comparisons with different demand patterns: smooth, irregular, slow-moving, mildly intermittent, and highly intermittent. In a mass-customization system, these considerations would be worthwhile to visit. 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 for remanufacturing in a push-and-pull combined system (Teunter et al. 2004). The goal was to propose a class of inventory strategies for this single-item hybrid inventory system with unequal lead times. The paper presents comparisons of the optimal strategies in classes of standard push, lead-time-adjusted push, standard pull, lead-time-adjusted pull, and separate pull. They conclude that the "separate pull" performs well in almost all categories. More research can be performed on separate pull in more complex inventory systems, for instance with stochastic lead time.

The ability to provide significantly high levels of customization at relatively low cost with regard to build-to-order (BTO) and value proposition was shown in Chakravarty and Kumar (2002), where BTO is in favor and make-to-stock (MTS) is out of favor.

Fogliatto et al. (2003) proposed a customization index to estimate the viability of implementing mass-customization systems. The index was based on three variables: (1) customer requirements, (2) supplier delivery flexibility, and (3) production flexibility. The index was implemented through an original application of the quality function deployment (QFD) matrix. The QFD matrix approach allowed the building of a customization index that incorporated both market and technical requirements. This index to each customization item (CI) was adjusted by importance (customer demand) weights and performance (product and process) weights. In a large, customized, integrated product system, QFD can be an effective approach to match customer desires with design configurations.

A paper that surveyed the literature on mass-customization from 1992 to 2001 provided two main contributions: a comprehensive guide that helps researchers to screen the vast amount of MC literature, and a research agenda covering a variety of important and unexplored facets of mass-customization (Da Silverira et al. 2001).

2.2 Supply-chain modeling

Fast reconfiguration among all entities in the overall supply-chain system is necessary to integrate customized products in a large assembly manufacturing system.

It was mentioned in Villa (2002) that the actual goal for effective supply-chain management is to obtain a good integration of all intelligent agents in order to make each local strategy as cooperative as possible. The paper presents a set of design criteria that could drive a designer to organize more efficient management systems. As a consequence, every manufacturing and distribution step, from raw material acquisition to final product delivery, should in principle be included in a supply chain, which should connect material suppliers, producers, distributors, and customers.

A framework of supplier-to-partner and supplier-to-supplier relationships to ensure traceable and customized products is depicted in a supply-chain management, interorganizational information system matrix (Shah 2002).

A survey of emerging research on the impact of e-business on supply-chain management including descriptive frameworks, analytical models, empirical analyses, and case studies is shown in (Johnson and Whang 2002), which enlists three major categories in the e-business supply chain: (1) e-commerce, (2) e-procurement, and (3) e-collaboration.

Forecasting and inventory control of customized components and spare parts presents a particular problem. In Mikkola and Gassmann (2003), Croston's method was modified and is referred to as the approximation method, which provided forecast results in handling spare parts that have an intermittent or slow-moving demand pattern.

To explore the linkage between supply-chain complexity and delivery, a two-dimensional framework is proposed in Vachon and Klassen (2002). This article conceptualizes the degree of complexity embedded in a supply chain along two major dimensions: (1) form of technology and (2) nature of information processing. A two-by-two framework was created to define supply-chain complexity and to provide a strong theoretical basis for linking different aspects of complexity to delivery performance. Their impressive process/product complexity and uncertainty illustrations did not mention issues relating to customized products. Thus, a research possibility exists in a multidimensional performance approach that includes customized product configurations.

Logistics support is a key element in the supply-chain system of customized manufacturing systems. In Cochran and Lewis (2002) they indicated such importance as seen in aircraft transportation systems. To optimize spare provision, they applied algorithms based on finite queuing theory instead of heavily relying on discrete event simulation.

The decision-support tool for supply chains through object modeling (DESSCOM) is illustrated in Biswas and Narahari (2004). DESSCOM provided a modeling infrastructure including a library of carefully designed generic objects for modeling supply-chain elements and dynamic interactions among these elements. Their modeling and analysis was done to gain a better understanding of the system complexity and to predict system performance, both critical in the system design stage and often valuable for system management.

2.3 Simulation

Simulation can be applied in this type of study, which seeks to optimize potential time and cost consequences of dynamic customized changes over given sets of predefined customizable design configurations.

Multiple runs of Monte Carlo simulation were applied to produce cost and duration distributions in the development process for a military product (Browning and Eppinger 2002). Iteration was addressed as a fundamental feature of the product development (PD) process. The model yielded and reinforced several managerial insights, including: how rework cascades through a PD process, trading off cost and schedule risk, interface criticality, and occasions for iterative overlapping. However they did not address potential applications to customized manufacturing aspects.

Simple++, a software product for planning and optimization developed by Tecnomatix Technologies, Ltd., was employed to conduct simulation in different systems where logistics coordination is a specification of a dependency at a certain moment in time (Verbraeck and Versteegt 2001). Important choices were made for the logistic control using functional decomposition and a decentralized, layered hierarchical approach. This decentralized approach made the control system scalable. Communication in their model was event-driven and only occurred when the control system or the equipment had reached a certain stage in the execution of activities. So they could minimize the amount of communication that was needed.

In modeling a large, complex system, Brailsford et al. (2004) describes how system dynamics was used as a central part of a whole-system review of emergency and on-demand health care.

Simulation modeling can also be accomplished via an object-oriented system-development approach. This type of model was referred to as the information systems development acceptance model (ISDAM) (Hardgrave and Johnson 2003). Product customization could have been integrated into this type of analytical approach, and may be further developed to include the level of customization.

Dynamic modeling of a production inventory system usually involves lead-time models (Wikner 2003). Three different approaches to continuous time dynamic modeling of variable lead times based on control theory are discussed in that paper. These three approaches to the lead-time modeling were: (1) first-order delay, (2) third-order delay, and (3) pure delay.

More research literature on the use of discrete event simulation for manufacturing system design and operation problems was reviewed and classified (Smith

2003). Three primary classes of research were considered in this article: (1) manufacturing system design, (2) manufacturing system operation, and (3) simulation language/package development for manufacturing systems applications.

In a semiconductor wafer factory simulation research, (Schruben and Roeder 2003) the execution speed of a resource-driven model was found to be insensitive to system congestion, whereas a job-driven model slows dramatically as the system becomes heavily loaded. They concluded that a resource-driven approach using event-scheduling logic offers the best approach to modeling very large scale, highly congested systems. Their finding was important in modeling low volume, high mix manufacturing systems.

3 Integrated system objects

Objects of mass-customized final products in an integrated system consist of multiple tiers of integrators, suppliers, and designers. These integrators, suppliers, and designers do not necessarily maintain one-to-one relationships. Some of the major component integrators may be suppliers to other integrators. Design activities also may take place at all levels in such integrated systems.

Producers of some of the non-customized common products may opt to design their own products. These producers often supply many major suppliers, who very possibly can be partners and/or competitors at the same time. Producers of customized products may design those products jointly with the final integrator, so relationships associated with participation and decision levels hardly will be a straight vertical integration or one-to-one, as seen in many traditional mass-production systems. Partnership relations are important since among the many factors in an integrated system, business plan, psychological factors, and operational issues are the three major reasons that Internet-based businesses fail (Linton 2003).

Three supplier-to-supplier relationship archetypes are discussed in Choi et al. (2002): (1) the competitive supplier–supplier relationship, (2) the cooperative supplier–supplier relationship, and (3) the "coopetitive" [concomitantly competing and cooperating] supplier–supplier relationship. Customized product development and manufacturing may involve all three of these relationships during different stages of the process. Team relationships can also be considered from the personality point of view in concurrent engineering, where project tasks generally involve the establishment of multifunctional design teams in order to simultaneously consider various activities throughout the entire product life cycle (Chen and Lin 2004).

One of the research papers contributes to the empirical examination of the idea that the communication frequency of cross-functional teams does not have a simple relationship with team performance. The paper examines the possibility that communication frequency has a curvilinear relationship to team performance (Patrashkova-Volzdoska et al. 2003). Their research could be extended to help the understanding of communication frequencies against customization level among suppliers.

When combined with appropriate social processes, it is indicated in Kock and Davidson (2003) that collaborative technologies may foster knowledge sharing.

Then the positive link between the use of collaborative technologies and knowledge sharing may offer more positive possibilities in customized product ordering and manufacturing.

Dynamic interactions, including technology collaboration and effective communications, have to be established in an integrated system of mass-customized large-scale assembled products. Customization factors and their respective importance in a large, integrated system can be regarded as different stages of interim products. They are categorized in three major levels: (1) system level, (2) component level, and (3) detail level, as outlined in Table 1. In a large-scale integrated assembly operation, no one entity is either practical or financially justifiable to produce millions of detail parts, to assemble them into subcomponents, to integrate them into major components, and to perform the final system integration and assemble them all independently.

The various stages of interim products among different levels are shown in Table 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. The customization factors at the detail level may consist of variable designs, 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 be few predefined basic component structures. Customization of these basic structures came from the already-defined subcomponents at the detail level.

Upon examination of stages of interim products within each level shown in the columns of Table 1, the major factors to consider at the system level are large-component assemblies, propulsion system, and final integration. As has been addressed above, no one entity can encompass all activities associated with large-scale customized assemblies. 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

Table 1 Customization factors

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

level, one must consider both the detail and the system levels in order to maintain the appropriate customized system hierarchy and agility. For example, large structural components and propulsion system components shall be fully stuffed and constructed prior to the final integration stage. 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 customized large-scale assembly operation provides the ability to make changes at various stages of the system with minimum disruptions of the final integration schedule.

4 Customized product configuration

Customer preferences for customized products 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. During this critical phase of product development, suppliers, designers, and the final integrators share mixed responsibilities based on predicted market trends and customer surveys.

In an example of one of the world's largest electronic systems of telephone connection switches, configuration can account for as much as 20% of the total product costs (Fleischanderl et al. 1998). The study shows that in addition to the component library and customer requirements, the set of reusable components was a necessary input to the configuration process. Costs as well as development and maintenance times were also crucial factors needed for success.

A sample framework of customized product configuration attributes is listed in Table 2. Product configuration attributes are listed as L1, L2, L3, P1, P2, P3, A1, A2, A3, etc. to reflect their levels in their respective interim product stages.

Contributions to each configuration attribute are developed and derived from multiple tiers of teams that generally consist of the final integrator, designer, and suppliers. Involvement and contribution from each team with regard to each customized final product attribute varies, depending on the main function of each team. Hence, the contribution from designer number one to the product configuration attribute L1 can be noted as L1D1. Similarly, the contribution from designer two to L1 can be noted as L1D2. This particular product configuration attribute L1, as seen in Table 2, is ultimately furnished by the supplier one, whose contribution is then noted as L1S1.

The same logic applies across the rest of Table 2. The significance of this type of customized configuration attribute arrangement is that impacts of all major players in the system are captured according to their contributions to each customized feature of the product. When this table is fully constructed, it will depict a cascading customization hierarchy, such that any product feature that is partially designed by one supplier and made by another with components from various vendors for a unique customer's customized requirements can be easily traced.

Table 2 Customized configuration attributes

Cnfg. attrib.	Final intgrtr.	Designer		Suppliers	
L1	L1F2	L1D1	L1D2	L1S1	
L2	L2F2	L2D1	L2D2	–	L2S2
L3	L3F2	L3D1	L3D2	L3S1	–
...	...	...	...	...	...
P1		P1D1			
P2			P2D2		
P3		P3D1	P3D2		
...	...	...	...	...	...
A1	A1F1	A1D1			
A2	A2F1		A2D2		
A3	A3F1			A3S1	A3S2
...	...	...	...	...	...

5 Customized design configuration decisions

Configuration decisions of customized product design for customer needs involve interactions beyond just those between the design and the marketing departments. For customized products that require large-scale assembly in an integrated system, each entity in the system has its own desired configuration decisions. Entities of such a system may consist of the final product integrator, designers, suppliers, and customers. Individual customer-preferred considerations of a customized configuration system are illustrated in Fig. 1.

Stummer and Heidenberger (2003) took into account theme profiles of the objectives, various project interdependencies, logical and strategic requirements, as well as resource and benefit constraints in describing a three-phase approach to assist research and development managers in obtaining the most attractive project portfolio. Comparable analogies can also be applied in customizing product design and configuration processes.

As indicated in Fig. 1, the design activity may have its own preference in order to optimize certain product features in the design process. When multiple exclusive suppliers are involved with different configuration priorities, design activities will then have to accommodate per suppliers' specialties. Consider two categories of suppliers, type I and type II. Some of the components can be mass-produced and some will need to be custom manufactured for supplier types I and II, respectively. Configuration management of customer-furnished components, which are purchased and often partially specified by customers directly from supplier type I and/or II and delivered directly to the final product integration location for customized assemblies, involve the customer, final product design, suppliers, and assembly capabilities. Assembly capability is one of the key considerations that cannot be ignored among the product configuration management, designers, and the final

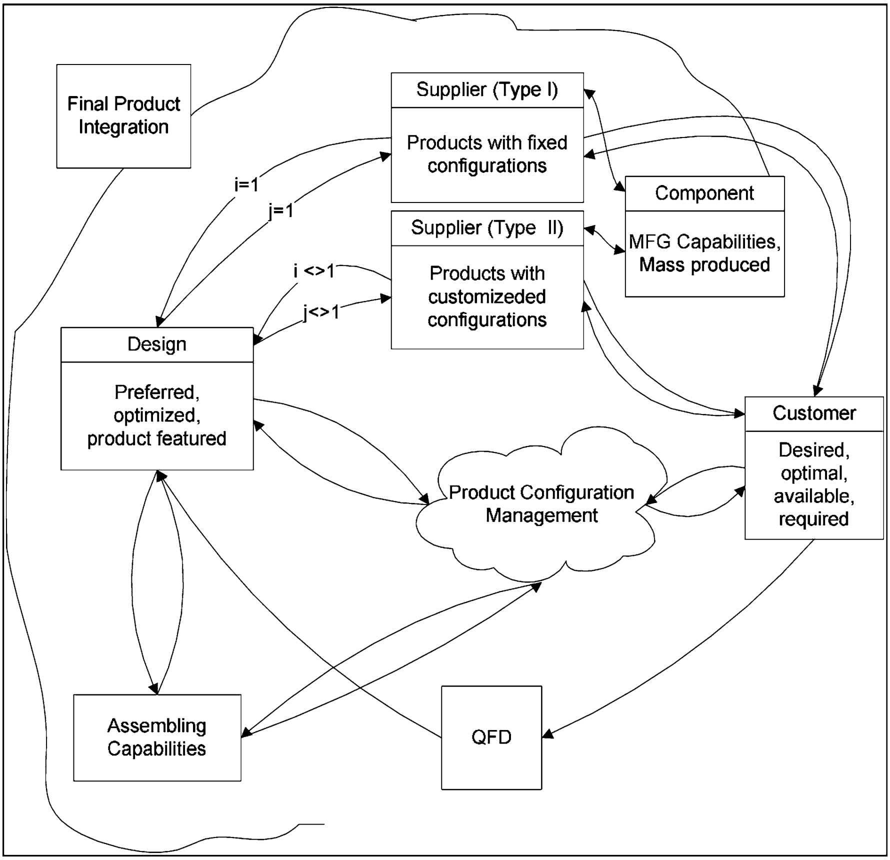

Fig. 1 Individual customer-preferred considerations of a customized configuration system

product integration. The customer's voice to the designers can be expressed in the form of quality function deployment (QFD).

Given the described product configuration-management-centered system for large, customized assembly products, the product structure of such customized assemblies is illustrated in Fig. 2. 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 rivets, can be mass-produced by sub-suppliers. There may be multiple tiers of end-item suppliers and sub-suppliers. Large-component assembly is likely to take place simultaneously at multiple geographical locations.

End-item (Ei) suppliers (Si), designers (Di), and the component itself (Ci) contribute to the level of interactions of each large component, LiXi. Multiple levels of interaction complexities (X1, X2, etc.) of the same large-component assembly, say L1, may have multiple suppliers (S1, S2, etc.), designers (D1, D2, etc.), and components (C1, C2, etc.). Based on such understanding, one can then derive a hierarchical structure of all customized large-component assemblies, defined in the following equation.

$$\sum_{i}\sum_{j} \text{LiXj} = \{\text{Ei, Si, Di, Ci}\}$$

6 Simulation modeling framework of the system

Dynamic interactions among all entities can be a challenge to represent via a statically modeled, deterministically customized, large assembly integrated system. A stochastic simulation modeling approach thus enables the appropriate framework to present such a customized system dynamically. This section discusses simulation elements, modeling approaches, and the system model framework of the subject system.

6.1 Simulation elements

There are several fundamental simulation elements in a discrete-simulation model. These simulation elements may be referred to as objects or modules such as sources, buffers, processes, machines, workers, material-handling systems, parts, sinks, batches, decisions, transporters, schedules, etc. To create a framework for a large, customized integrated system, these simulation modeling objects need to be assigned appropriately. Basic functions of simulation elements are listed in Table 3.

Customized product handling in simulation models requires disciplined arrangement, because almost all end items need to be traceable in most large-scale

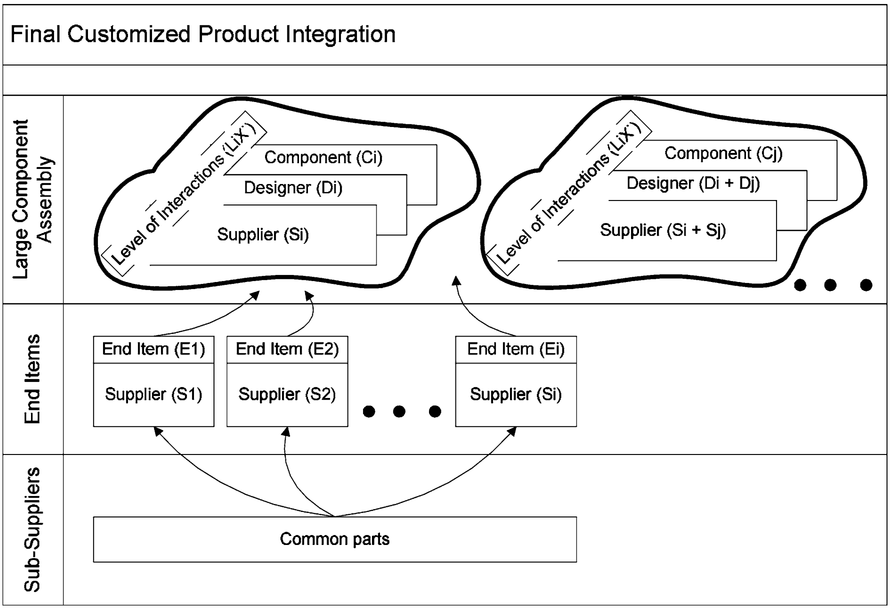

Fig. 2 Customized product structure

Table 3 Simulation elements

Modules	Functions
Part/entity	Represent end items and components
Schedules	Govern release times of parts
Create/source	Generate parts per schedule
Buffer	Store inventory parts
Process	Specify resource and part needs
Worker	Persons needed for processes
Machine	Make/assemble parts per processes
Transporter	Relocate parts
Batch	Group parts together
Destroy/sink	Terminate parts in the system
Assign	Provide attributes to parts
Record	Register statistical information
Separate	Reverse the batching process

customized assembly manufacturing processes. Since mass-produced end items are not covered in the simulation of this customized large-scale system, traceable component batching from different suppliers with respect to their part transportation logistics has to be maintained. Therefore, a serial number for each entity in the system is needed among all modules for traceability and control.

6.2 Modeling approaches

As compared with a straight-line manufacturing process using a discrete event-simulation modeling approach, this system needs multiple parallel processes linked with dynamic interactions among process modules. The performance and behavior of the process modules are influenced dynamically by routine system events and dynamic customized events that take place statistically and randomly with certain distributions. Given the interactive nature of the system, it is desirable for the modeling approach to be interdependent among modules as much as possible, based on customized events distributed over a given time span.

The most statistically stable module is the master production schedule for the product final assembly sequence. This master schedule is based on the desired final product delivery dates that are predetermined by customers during the product ordering process. It is common to have master schedules across several product families cover several years of production time in a large, integrated manufacturing system. Customized component production schedules that cascade down from master schedules can be determined via a traditional material requirement planning (MRP) system, or in this case, dynamically determined, based on statistically validated historical data. Therefore, entries in master schedules will drive entries in customized component schedules based partially on their directly non-weighted lead-time relationships and, more importantly, on the status of various related system events that are captured in the form of statistical distributions.

The ability to observe compounded customized change effects dynamically is one of the important features that needs to be intelligently presented in the modeling approach. System entities are to be treated as individual objects whenever possible. These individual objects are represented mostly as individual electronic files in today's computing environment.

A multi-thread type of simultaneous parallel file access architecture is necessary to enable dynamic system information updates among system objects. The level of simultaneous updates may be governed by a "heart-beat" rate routine that initiates the refreshing of associated objects and contents of electronic files. This capability is essential in stochastic modeling of customized large-scale integrated assembly operations.

6.3 System model framework

The framework in modeling a system for large assembly manufacturing of customized products requires management of manufacturing and supply-chain logistics, product launch, design planning and scheduling. It also requires the ability to change to reflect market trends, statistically stable and predictable measurable performance throughout the system, pull and push of mixed logistics in the whole system, and control of the time factor. All of these framework considerations are shown in Fig. 3.

Planning a customized product design is often market-driven, thus it is normally scheduled backwards. Demand for most large-scale integrated products, such as airplanes and ocean vessels, relies heavily on regional and global economic stability and growth possibilities. Demand is also often cyclical in the range of decades, not just years. Thus, the planning and scheduling part of the framework goes backward from the forecasted final product delivery to the end-item logistics.

The traditional manufacturing system ordinarily progresses according to established planning and scheduling. In a supplier-involved, dynamic mass-customized system, both pull and push 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 needed large components in a timely manner. Most large-scale system integrators of customized assemblies strive to minimize the "make-span" 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. The feasibility and cost effectiveness of further customizing already assembled products beyond the final product integration can be very unfavorable.

The schedule from end item to the final product integration, as shown in Fig. 3, is said to be developed backward as part of the planning activity. The ability to change levels of product customization according to the schedule status along the product integration time scale varies because of constraints imposed by statistically stable and predictable end-item/component/final product customizable feature distributions.

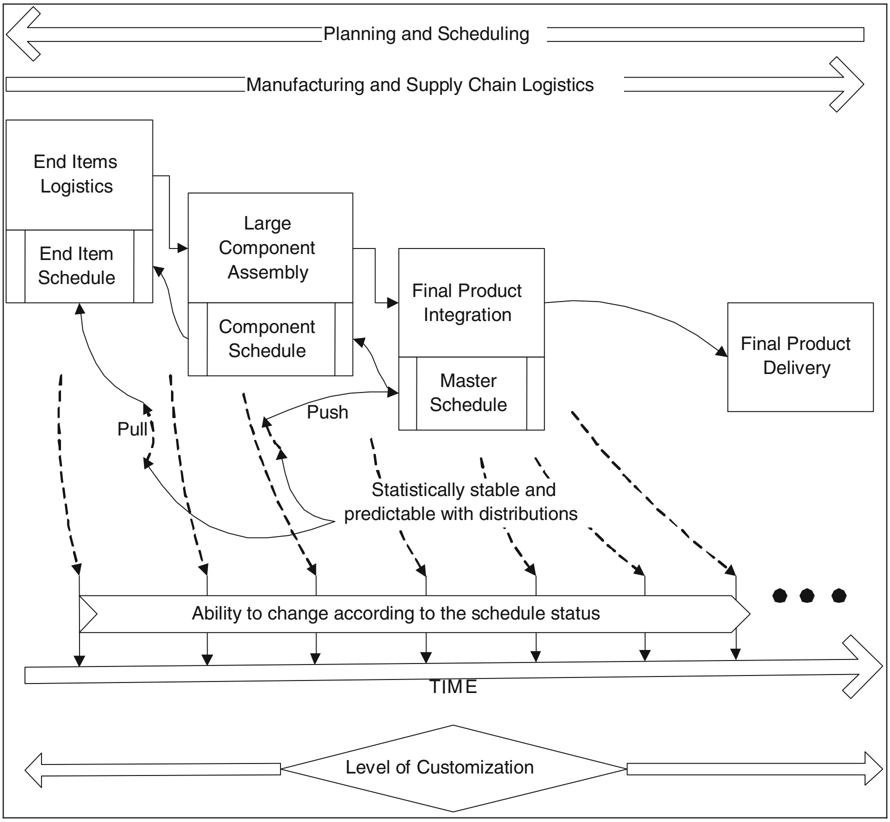

Fig. 3 System modeling of a customized product supply chain in a large, integrated system

If this framework were applied to new product launches, timing associated with customized product design by the final integrator and all tiers of suppliers must be statistically dependable. The associated parties receive the time scale via a predefined information flow chain that shares common and secure communication protocols. Such a design information chain shall be regarded as the necessary condition for a new product launch system model framework. As described earlier, the same product sections can be designed by multiple parties and custom manufactured by the same or different parties in the system.

One goal of utilizing this framework is to simulate cost and time decisions as a function of customization levels and change effects, based on product configurations. Employing simulation technology not only allows one to observe customized large assembly manufacturing activities across the whole supply chain, but it also enables more statistically reliable forecasts of effects caused by impromptu, customized changes made during the whole product integration cycle. This framework describes a system architecture that models statistically controlled, dynamic customization approaches in a large-scale integrated system of customized product assemblies.

7 Case study

7.1 Introduction

Aalborg Industries A/S is an international company specializing in steam and heat generating equipment for maritime and industrial applications. The main product types include steam boilers, waste heat recovery boilers, heat exchangers, burners, control systems, thermal fluid systems, and FPSO heating solutions. In some cases these components are sold separately, but often a whole system is supplied to the customer where several of these components are combined. Components and solutions for marine applications constitute approximately 85% of the total annual sales, and the remaining 15% is sold for industrial applications. The Danish-based company had a turnover of US$280 million for the year 2005 and employed 1683 people worldwide at the end of that year.

Aalborg Industries, which has traditionally been an engineer-to-order company, has for a period of time been working toward the mass-customization paradigm to reduce cost and improve quality and business process efficiency. As a part of this effort the product portfolio has been consolidated and standardized while modular product structures have been introduced. As a means to achieve mass-customization, technologies such as product configuration systems have been implemented to support the sales process as well as the engineering and manufacturing phases.

7.2 Supply-chain structure

Since the main customer group of Aalborg Industries consists of shipyards, this particular business segment was used in this case study.

Figure 4 is a simplified illustration of the supply chain used for building a new ship. Aalborg Industries typically acts as a supplier to shipyards supplying steam boiler plants to the shipyards for installation in new ships which have been pre-sold to a shipowner. However, in some cases Aalborg Industries may also sell a steam boiler plant directly to the shipowner. Figure 4 is not a complete representation of the shipyard's supply chain, and is simplified to illustrate basic principles centered around Aalborg Industries. In practice the shipyard will have hundreds of suppliers involved in the production of a new ship.

Considering the boiler plant system, Aalborg Industries acts as the final integrator of all of the components that make up the system. Aalborg Industries' suppliers can be segregated into two main categories: raw material suppliers and integrated component suppliers. The raw material suppliers provide materials such as steel plates, valves and other commodities that can be purchased from several different suppliers, and no design and integration is required. The integrated component suppliers furnish more complex components for the steam boiler plant such as burners and control systems, which must be designed for use with Aalborg Industries steam boiler plants and may be specially designed for use with a specific plant. Some of Aalborg Industries' suppliers market products which are substitutable with certain products that Aalborg Industries sells. However, these are not

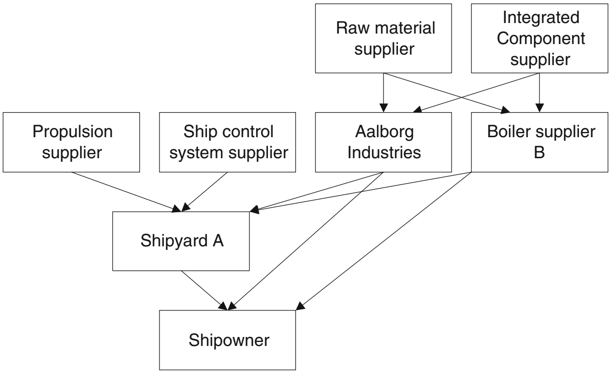

Fig. 4 Simplified model of the shipbuilding supply chain illustrating the relationships to Aalborg Industries

whole steam plant systems but merely components included in the system. Based on this, it can be concluded that Aalborg Industries has a "coopetitive" (concomitantly competing and cooperating) supplier–supplier relationship with some suppliers as outlined in Sect. 3, while the relationships to other suppliers are strictly competitive or cooperative. Other companies supplying steam boiler plants are examples of the competitive supplier–supplier relationship, as there is no cooperation between Aalborg Industries and other companies delivering steam boiler plants.

Aside from the supplier–supplier relationships described above, Aalborg Industries also has a "coopetitive" supplier–supplier relationship with a number of their customers, in that some of Aalborg Industries' customers themselves manufacture boilers. This means that in some contexts Aalborg Industries collaborates with these companies as a supplier, and in some other cases Aalborg Industries will compete with these same companies while bidding for a sales contract. Aalborg Industries' relationship with its customers is comparable to the relationship between jet engine manufacturers and passenger aircraft manufacturers in that only a few larger steam plant manufacturers exist, and Aalborg Industries supplies equipment for virtually every shipyard worldwide. During the sale, engineering, and delivery of a steam boiler plant, Aalborg Industries works closely with the customer to tailor the steam boiler plant to meet the requirements of the customer and to integrate the plant into the other systems in the ship.

From the description of the supplier and customer relationships above, it can be concluded that the supply chain which Aalborg Industries is a part of when supplying a boiler for a new ship is a complex network with multiple tiers of integrators, suppliers, and designers that indeed does not have a one-to-one supplier–customer relationship.

7.3 System integration stages

As outlined in Sect. 3, in a large-scale integrated assembly operation no one entity can produce detail parts, assemble them into subsystems, and finally combine them into a large, integrated system. This is also true for ship production, since systems such as propulsion systems, electronics, and steam boiler plants are almost always designed and manufactured by companies separate from the shipyard.

In this case the shipyard will usually work as the integrator as well as the manufacturer of the ship hull. The subsystems which the shipyard does not have the financial or technical capability to design and manufacture are procured from a sub-supplier. Considering the example of an oil tanker, these subsystems include but are not limited to the following:

- Propulsion system including main engine, propulsion shaft, and propeller.
- Cargo loading and unloading system.
- Control system including navigation and communication equipment, and rudder control systems.
- HVAC system.
- Steam system including oil-fired steam boilers, waste heat recovery boiler, steam lines, and consumers.
- Bow thrusters.
- Electricity generator systems.

Each of these subsystems must be integrated into the ship system to successfully produce the oil tanker.

Figure 5 illustrates the different integration tasks that are related to the production of a steam boiler plant and ultimately the integration of the steam boiler plant in a ship system. Each of the main components in the steam boiler plant is designed and manufactured by the integrated component supplier. For some or all of the main components Aalborg Industries also acts as the integrator of the subcomponents, since a number of these components are designed and manufactured in-house.

Aalborg Industries performs the final integration of the steam boiler plant, ensuring that all subcomponents work together, and acquires the class approvals that are required by the customer.

As a part of the final integration of the steam boiler plant, Aalborg Industries is usually responsible for commissioning the steam boiler plant once it has been installed in the ship. This process ensures that the boiler plant is integrated with the environment it is working in, which in the case being described here is a newly built

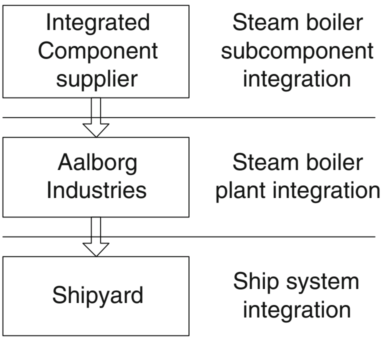

Fig. 5 Integration of systems at different stages

ship. The overall responsibility for integrating the ship system lies with the shipyard. In the final integration of the ship system, the shipyard incorporates the major components of the ship, which besides the steam boiler plant includes the hull, the propulsion system, control system, and electrical system, as well as numerous other systems. As with the steam boiler plant, the ship is also classified by a classification society according to customer requirements. Once all this has been done, the final integration is concluded with a sea trial where all systems are tested.

7.4 Customization factors

When a customer orders a new ship, the customer will specify a number of requirements for the ship as well as for some of the ship's equipment. In Fig. 6 a sample breakdown structure of a ships subsystems is shown, simplified to emphasize the relations to the steam boiler plant. As shown in the figure, the steam boiler plant is a part of a larger system, namely the steam system. The other subsystems of the steam system have interfaces to the steam boiler plant, and they must therefore be integrated. In this particular case, the integration involves dimensioning the steam boiler plant with the capacity to supply the amount of steam required at the required pressure. The integration of the steam line is a matter of dimensioning the piping to deliver the produced steam and return the condensed steam to the steam boiler plant.

Often, the tightest complex integration between systems is between systems that are subsystems to a common system. One example of this type of integration is the integration between the steam boiler plant and the steam consumers. However, integration is in some cases also required between systems that are subsystems of different systems. One example of this is the WHR boiler system that must be integrated with the propulsion system. The WHR boiler system utilizes the heat from the main engine exhaust to heat or boil water, thereby reducing the amount of oil

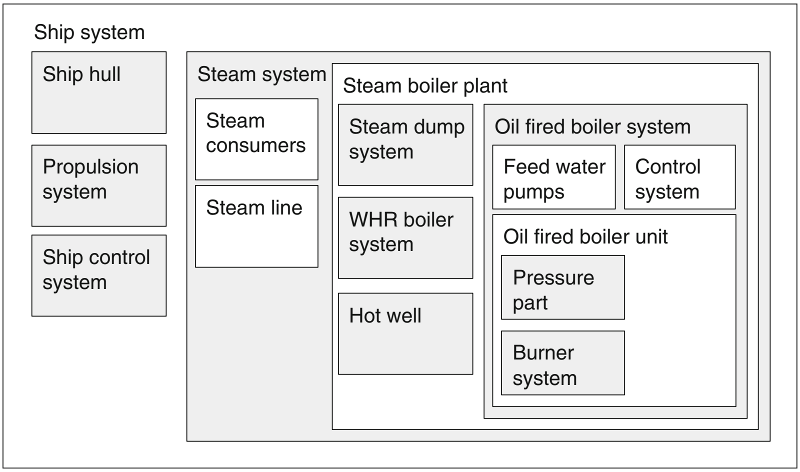

Fig. 6 Simplified system hierarchy of the steam boiler system with super- and sub-systems

consumed to generate steam. The WHR boiler system must be designed according to the characteristics of the main engine exhaust gas, which include mass flow, exhaust gas temperature, and maximum allowed pressure drop across the WHR boiler.

Examples of how the subsystems in the ship are integrated within a single system as well as across different systems can be found in many cases. Often the systems are designed according to direct specifications from the customer, which means that the design, manufacturing, and integration tasks depend to a high degree on the different customization factors.

In Table 4 a selection of customization factors are illustrated according to the framework proposed in Sect. 3. Each row represents an interim product, with different levels; system, component, and detail level. The systems in each row are not strictly sequential, in that the propulsion system and the steam boiler plant may be designed and manufactured concurrently. However, they must be designed completely prior to the final integration of the ship system.

Examples of customization factors in the final integration include details such as crew cabin furnishing and galley layout and equipment. The reason for these factors being in the final integration phase is that these can be installed after the ship has been built and proven seaworthy, and no activities prior to the installation depend on the customization factors. Also in the final integration phase, a number of systems are calibrated or commissioned. These include but are not limited to propulsion systems, control systems, and steam boiler plant adjustment. In order for the steam boiler plant to work efficiently, calibration and adjustment are often required.

The steam boiler plant itself is included in Table 4 as an item on the system level. The component-level customization factors are of the capacity and boiler type, since

Table 4 Example of customization factors for an oil tanker and a steam boiler plant

Stages of interim products		
System level	Component level	Detail level
Large hull sections	Basic structure	Custom design
		Repeatable sections
		Substructures
Propulsion system	Power	Oil filters
	Engine type	Coolers
		Control system
Steam boiler plant	Capacity	Valve placements
	Fuel type	Valve types
	Boiler type	
...	...	...
Final integration	Accommodation quarters	Crew cabin furnishing
		Galley layout and equipment
	Systems calibration and commissioning	Propulsion systems adjustment
		Control systems configuration
		Steam boiler plant commissioning

these are used for determining the basic design of the steam boiler system. Also the fuel type used for the steam boiler plant is a constraint for boiler construction, and therefore this is also a major customization factor. At the detail level, customization factors include details such as valve placements and valve types. These customization factors are less complex than the ones at the component level in the sense that the values of these factors do not affect other systems or customization factors significantly.

If a matrix of customization factors was constructed full-scale for a new ship, it would be far more complex than the simplified version illustrated in Table 4 and would include thousands of customization factors, as well as a significantly higher number of systems at the system level.

7.5 Case study simulation

A series of simulation models are constructed to simulate the case study in conjunction with the stated framework. Since every component has its own serial number attached as an attribute, each component is created individually in step 1 as seen in the Fig. 7. The learning curve 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 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.

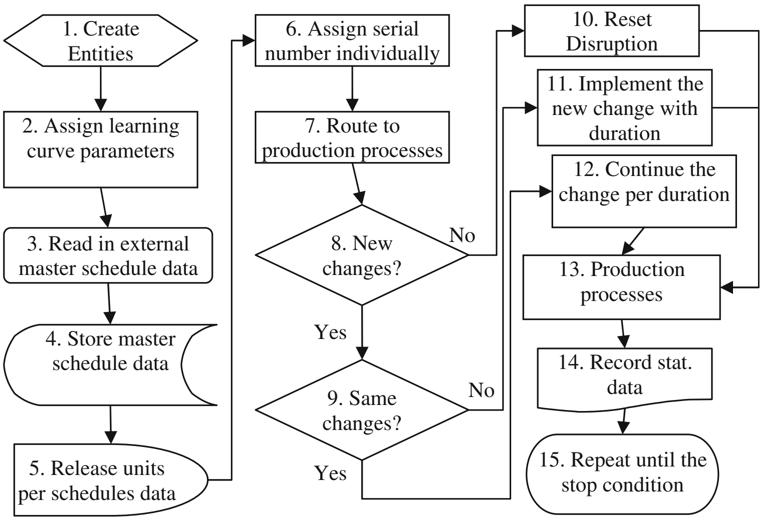

Fig. 7 Simulation method high level flow diagram

Steps 8 and 9 check for any 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.

In the simulation model, there are thirteen detail level products, such as oil filters, coolers, valve types, crew cabin furnishing, etc. There are five component level products, such as basic structure, power engine, boiler, systems, and accommodation quarters. There are four system level products, such as large hull sections, propulsion system, steam boiler plant, and the final integration.

Figure 8 simplifies a real large-scale production system into a conceptual model frame of the system structure. Gate 1 happens right around the time when the work order is released, gate 2 takes place in the middle of a major component production, and gate 3 is right before the final integration. At any given time all suppliers perform at different locations on their learning curve, as shown in the diamond shape dots. Hence, customer decisions at different gates produce un-equal system impacts all the way to the final integration, per component and per supplier.

All elements in the system are modeled using the discrete event simulation method. Elements in the system are connected according to both the information flow and component flow networks, in which all are operated on one master production schedule. Each component unit has its own production starting time, which is reflected as in the gate 1 zone. Each component process has its unique process characteristic of different progress rates. The gate 2 zone resides within each component unit processes times. In an ASLC featured system, component unit process progresses vary from component to component. The diamond-shaped dot within each supplier's process box in Fig. 8 represents process status on its learning curve for that supplier. Suppliers are not likely to have their processes status on the relatively same learning curve locations in a system that is both asynchronous and stochastic. The gate 3 zone is before the

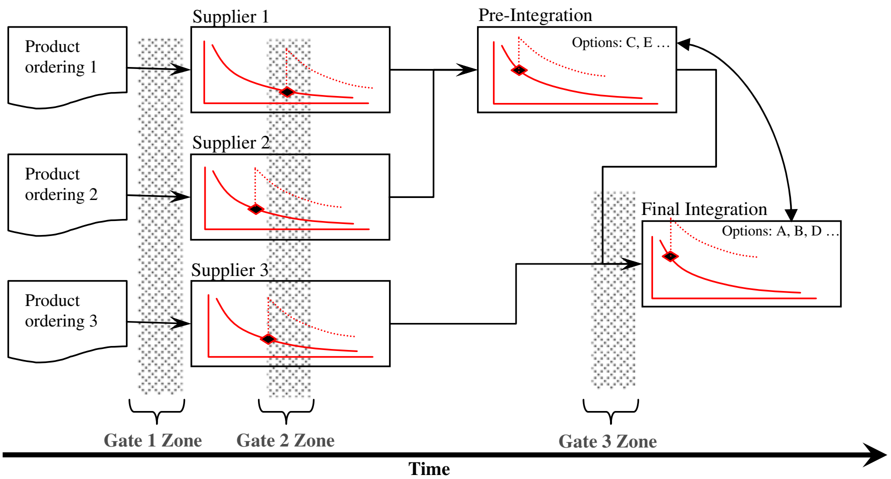

Fig. 8 A simulation model of a production system example with decision gates

starting of last group of process times in the final integration and at the same time some of the component unit processes are still taking places. Thus, some of the component finish times are overlapped with the decision triggering time in the gate 3 zone. It is intuitively reasonable that component customization decisions are the least desirable to trigger during the gate 3 zone.

Three stages of interim products were mentioned earlier. Figure 9 shows processes in a simulation model where both system and component levels (category 1 and 2 in Fig. 9) customized selections take place earlier in the final integration. Their respective customized works are performed during the early stage of the final integration. Detail level (category 3 in Fig. 9) related selections happen too late in the system and can only be performed near the end of the final integration. Figure 9 is a more detailed view of processes among final integration and final testing and delivery as depicted earlier in Fig. 3.

Customization decisions triggered earlier among all three gate zones have different levels of influences among category 1, 2, and/or 3 processes during the final integration. Over the left side in Fig. 9, a series of component attributes are assigned in Assign modules in the DES model. In the middle of Fig. 9, a large dot-shaded box represents the Final Product Integration group of processes. Over the right side in the figure, another large shaded box represents the Final Product Delivery group of processes. Category 1 and 2 processes are all within the Final Product Integration process group. Category 3 processes, however, are spread across both the Final Product Integration and the Final Product Delivery groups of processes. Process times and occurrences in Fig. 9 depend on customization decisions made among those three gate zones. Some of the category 3 processes will take place when certain component units are in the final product integration and most of the category 3 related processes are done in the final product delivery group of processes.

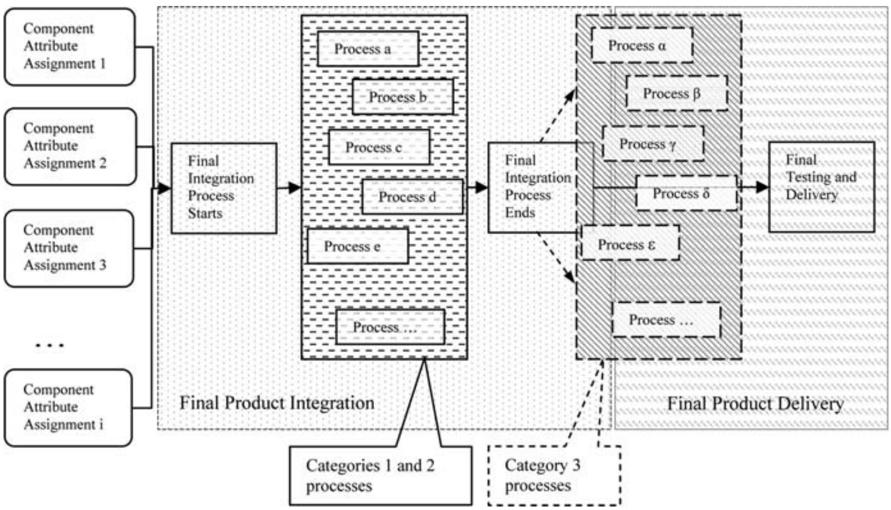

Fig. 9 A case model of processes in final product integration and delivery

Table 5 Case study process scenarios

Scenarios	A (%)	B (%)	C (%)
Gate 1	25	15	100
Gate 2	50	15	0
Gate 3	25	70	0

In this case study, three different scenarios are simulated with different decision percentages at each decision opportunity. Table 5 lists differences among these scenarios, the respective location of these gate zones are demonstrated in Fig. 8.

Gate 1 is right after the product ordering event. Gate 2 is in the middle of a component production process. Gate 3 is at the end of all component processes and just before the final integration. Scenario A: 25% of the customization selections are made at the gate 1, 50% at the gate 2, and 25% at the gate 3. Scenario B and C have different percentage selections at different gates as seen in Table 5. In the simulation model, these decision percentages are represented by three decision variables with discrete distribution targeted at their scenario percentages.

Disruptions happened at three different gates to reflect major product customization events and/or major design changes. Design changes can be a derivative product and/or a minor product model release in the middle of processes when the other models are being built. Process times in these two final stages contain all of the customization work statements that are selected among any of the three gate zones. Simulation modeling results, based on three customization scenarios in Table 5, of the processing time during a given final integration stage of the whole system are shown in Fig. 10. Process time in Fig. 10 is the sum of process times of all customization and regular processes in the final product integration and the final product delivery.

In Fig. 10 the y-axis is in log scale, based on scenarios defined in Table 5, scenario C has the least disruptions to the final integration processes while scenario B has the most. Discrete simulation modeling findings in this case study have also shown 150–200% process time increases are possible for demanding product customizations. The 150–200% process time increases from scenario C to scenario B happen around 1,400 and 1,450 calendar dates. Scenario A result lies between the other two scenarios as expected.

7.6 Case study conclusion

The case study presented above illustrates the example of Aalborg Industries, which is a steam boiler plant manufacturer acting as a supplier of subsystems to shipyards. In regard to the design of the boiler plant system itself and integration of the subsystems, the boiler plant is a subsystem to the ship system, which is designed and finally integrated by the shipyard. Furthermore, it was illustrated that the supply chain does not have a simple one-to-one relationship between suppliers and customers, but does to a greater extent resemble a network of suppliers and customers. The simulation model represents a small portion of the whole system. Customization decision influences to the system can be easily seen from the

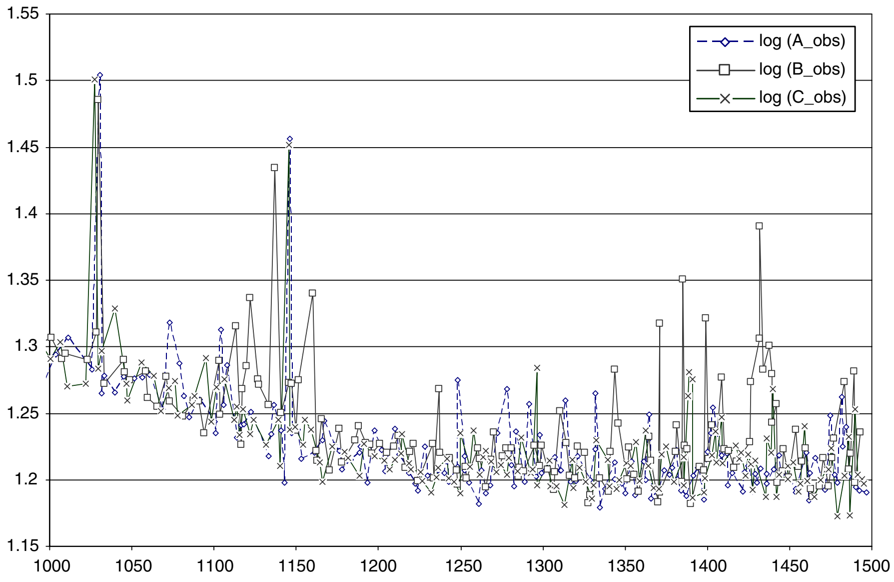

Fig. 10 Process time of the final integration for all three scenarios

simulaton model results. These suppliers also act as designers and integrators of subsystems, and it was illustrated in the case study that customization factors exist in different systems and at different stages, hence these are customized by different organizations.

8 Discussion

Ever since the industrial revolution, fabrication of modern products has evolved from custom manufacturing, to mass-production, and on to today's mass-customization. Trends of mass-customization and personalization have been evident not only because most people prefer personalized product features, but also thanks to the modernization of enabling technologies in manufacturing, design, and logistics. Product configurations determine the level of customization and associated cost impacts, especially when design, component fabrication, and final product integration can be performed at various locations globally.

Product vertical integration among tiers of suppliers, design houses, and final assembly integrators once may have been considered a modern manufacturing system structure. Today, thanks to the broad use of the Internet, concurrent engineering capabilities have been elevated for all parties. Customized design activities among suppliers and customers have become more integrated than ever.

To adequately identify the types of problems or deficiencies which can adversely affect coordination despite the development of optimal modes and levels of integration in current engineering, Sherman (2004) proposed that the development of optimal modes and levels of integration will not necessarily minimize these types of problems (technology transfer versus high performance). Rather, the achievement of optimal modes and levels of integration represents a necessary but insufficient condition for high levels of performance. They concluded that there is ostensibly a limitation of the investigation in managing deficiencies; i.e., there was insufficient evidence to support the hypothesis that the optimal group had fewer problems than the suboptimal group.

Simulation modeling can be applied as a powerful tool to oversee, examine, and predict possible effects of different design configurations and different combinations of supplier assignments of mass-customized products that require large-scale manufacturing assembly integration. Scenarios to model using simulation in this type of system can be divided into, but not limited to, the following categories:

- Product time to market-based on various design configurations.
- Logistics performance-based on levels and complexities of supplier involvement in both design and manufacture.
- Time and cost consequences, based on given levels of product customization configurations and relative sequences, and schedules of multiple customization requests during product fabrication processes.
- Overall system performance, based on choices of suppliers and their respective levels of involvement.
- Component transportation logistics, based on product-configuration-driven supplier allocations.
- Miscellaneous end-item, component, and final product integration manufacturing and business processes.

Effectiveness of the system does not solely rely on any single group of activities, not to mention on performance of a single entity in the system. It is necessary for all entities to perform to gain effectiveness. Appealing customized product design normally would be more promising in increasing market share, but only if the rest of the system can be managed and planned cohesively in an ever changing dynamic and balanced manner. The ability to allow customized changes throughout the product logistics time span must take all individual entities and the overall cohesiveness of the system into account. The cost of issuing customized changes at various critical points of the system varies drastically depending on the status of the product integration and initial design configurations. Timing of change in a mass-customization system is a function of cost and schedule. If products that require large-scale assemblies and integration were designed in configurations that made future dynamic customized changes difficult, no matter how individual entities may perform or how efficient the supplier logistics may function, the whole system would not be able to act and react fast enough to take advantage of positive market opportunities.

9 Conclusions

This research explores a fundamental framework that captures the requirements for a large assembly manufacturing system of mass-customized products with supply-chain considerations. Large-scale assemblies demand unusual support from infrastructure providers, hence stages of various interim product levels in this framework need to be considered accordingly. Once levels of interim product stages are orchestrated, levels of design and manufacturing responsibilities will be the next endeavor to overcome so the customized configuration attributes among designers and suppliers can be defined. Individual customer-preferred considerations for a customized configuration system will then be able to be integrated into the system. Thus, product structure hierarchy of customized final integrated products and their respective major components can be constructed in detail. Consequently, attributes of objects and parameters of the model can be addressed with consideration to the customized product supply chain in a large, integrated system.

Future studies based upon this framework will focus on the areas of higher fidelity definition of simulation parameters, statistically predictable consequences of individual entity performance under mass-customized change, and the means to provide predictable system time and cost performance within ascribed confidence levels.

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Author Biographies

Roberto F. Lu received his Bachelor's degree in Materials Science from Feng Chia University in Taiwan; first Master's degree in Mechanical Engineering from Marquette University in Milwaukee, Wisconsin; second Master's degree in Industrial and Systems Engineering from Virginia Tech in Blacksburg, Virginia; and third Master's degree in Industrial Engineering (IE) from University of Washington (UW) in Seattle, Washington. He is also enrolled in the Ph.D. program in IE at UW while working full time at Boeing.

Roberto is an Associate Technical Fellow with The Boeing Company, Commercial Airplane Material and Process Technology Organization in Seattle. His recent work and research is in areas of job shop, continuous flow, and large-scale system integration-related discrete event simulation, logistics, process optimization, lean manufacturing, and mass customization. He supports the 777 final assembly, six sigma and lean, manufacturing, the 787 program by modeling the 787 global production system, and the DreamLifler (Large Cargo Freighter) global logistics. He has supported: Wing Responsibility Center, 737, 747, 757, 767, 777, 787, Boeing Portland, Boeing Anaheim, Boeing Mesa AZ, Boeing Australia, Boeing partners in Italy, Japan, and South Carolina, all Boeing Puget Sound sites, and the Sonic Cruiser. Roberto has been invited to present his work at professional conferences worldwide, focusing upon discrete event simulation modeling, analytical process optimization, lean manufacturing, mass customization, and robotic applications. His professional career prior to Boeing includes experience in machine vision integrated robotic automation, product tooling development, product GD&T establishment and inspection, non-destructive testing in UT and RT, metallurgical spectrographic analysis, and manufacturing statistical quality control at the Pilkington North. America Libbey-Owens-Ford company and the Intermet-New River Castings company. Roberto is a member of SAE, ASME, and a senior member of 11E.

Thomas Ditlev Petersen is Master of Science in Engineering and holds currently an industrial Ph.D. scholarship. He is employed at Aalborg Industries A/S and related to Department of Production at Aalborg University. The industrial Ph.D. project he is currently working on is to document the challenges that engineer-to-order companies face when implementing mass customization and product configuration in particular. Included in this work is analyzing the need for new methodologies for product family and information modeling for this particular purpose.

Richard Storch is a Professor of Industrial Engineering at the University of Washington and has been the Director of lE since 2003. He has been on the faculty at the University of Washington since 1978. Before his academic career, Dr. Storch worked as a naval architect for The Glosten Company in Seattle for six years, as a staff member of the Council on Environmental Quality in the Executive Office of the President, and as an officer in the U. S. Coast Guard, stationed in the Merchant Marine Technical Branch in headquarters in Washington, D.C. In addition to teaching general courses in Industrial Engineering, he has been conducting shipbuilding productivity research through the National Shipbuilding Research Program since 1980. He has been a consultant to dozens of U.S. and a number of European shipyards. His primary areas of interest have been dimensional control, production planning, design for production, mass customization, and work organization. Dr. Storch is a fellow of SNAME, and a senior member of ASNE and HE. He is the Technical Editor of the *Journal of Ship Production*, and a member of the editorial board of the *International Journal of Marine Science and Technology*, and is on the international program committee of ICCAS (International Conference on Computer Applications in Shipbuilding) and of the IFIP WG 5.7 conference on Advances in Production Management. He is the lead author of the book *Ship Production*, as well as over 50 papers and reports. Dr. Starch received a Bachelor's degree in Naval Architecture and Marine Engineering from Webb Institute, a Master's degree in Ocean Engineering from Massachusetts Institute of Technology, and a doctorate in Mechanical Engineering from the University of Washington and. is a Professional Engineer registered in the State of Washington.