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Impact of Employing Mass Customization in Shipbuilding

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조선에서 대량 맞춤화의 영향

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ABSTRACT

One of the goals of mass customization is to permit changes in the product to meet specific customer requirements without substantially impacting the cost or delivery schedule. In large assembly manufacturing industries, such as shipbuilding and commercial airplane production, customization takes place by changing components and/or modules, sometimes called interim products. Using shipbuilding as a case study, it is possible to study the impact of such changes using mass customization principles on the schedule. In large assembly manufacturing, mass customization changes would cause changes in engineering time and production time, based on the amount of change required by the customization. This work first proposes a structure for implementing mass customization in shipbuilding and then uses simulation of a simplified, theoretical shipbuilding process to evaluate the impacts of various levels of change on delivery performance.

Key words : Mass Customization in Shipbuilding, Simulation Model of Shipbuilding, Group Technology

요 약

대량 맞춤화 생산에서 목표 중 하나는 생산 비용이나 제품 인도 스케줄을 크게 변화시키지 않고 특정 고객의 요구를 만족시키는 생산을 달성하는 것이다. 조선 · 항공과 같은 대형 조립-생산 산업에서의 맞춤화는 이에 따른 부품이나 또는 부품의 중간 조립품인 모듈의 변화를 가져오게 된다. 본 연구는 조선 분야에서의 사례 연구를 통하여 고객의 맞춤화에 따른 생산 스케줄의 변화가 선박 인도에 미치는 영향을 분석하고자 한다. 대단위 조립 생산에서 대량 맞춤화는 맞춤화의 요구 수준에 따라 엔지니어링 및 조립-생산 시간이 변화한다. 본 연구는 조선 산업에서 처음으로 대량 맞춤화를 수행하는 생산 방안을 제안하고 이론적 조선 생산 과정을 간략히 기술한 시뮬레이션 모형을 통하여 다양한 수준에서의 대량 맞춤화가 선박 인도 일정에 어떠한 영향을 미치는가를 평가하였다.

주요어 : 조선에서의 대량 맞춤화, 조선 시뮬레이션 모형, 그룹 테크놀로지

1. Introduction

In assembly production, one of the principles for effective mass customization is to employ common modules in different end products. However, the method of establishing common modules for large assemblies has not been clearly defined. In order to be effective in assembly productivity, the process must remain relatively stable. That is, the components of the final product (i.e. a ship) must be able to be assembled in a mass production like way. For assembly of these mass customized interim products, the work content, the work skills and the tools of production must be similar. In that case, the “customized” interim product can be assembled in the same work station, using the same workers and tools, and they will enable the process to have consistent, predictable flows. Thus, the final product (the ship) can be customized by applying the principles of mass customization at the

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component and/or sub-assembly stage. The manufacturing system sees only small changes associated with the different processing times for the customized components and/or sub-assemblies. The overall flow of work, with multiple sub-flows serving the final block assembly flow, is relatively unchanged by the customization of interim products. Thus overall productivity is maintained by maintaining a consistent production process.

There are a large number of questions that remain unanswered concerning the application of mass customization to a large assembly industry, like shipbuilding. Among these are the amount and place in the process in which mass customization can be implemented. Ultimately, the decision to employ the principles of mass customization will be based on overall improvement in cost and schedule for delivery of products (i.e. ships) that achieve customer satisfaction. This paper will consider some of these issues. Initially, ideas for how to implement mass customization in the shipbuilding process will be presented. Based on those ideas, a notional shipbuilding project will be used to evaluate the impacts of employing mass customization in the project. This will include a simplification of the process to a high level view. Then assumptions of the level of customization in design and assembly effort will be made. Because mass customization is assumed to be employed, learning curve improvements will be assumed to occur as additional ships are built. Finally, a simulation model of the process will be developed and run to evaluate the impacts of various levels of change employing mass customization on the on-time delivery percentage over a large number of projects.

2. The Shipbuilding Process

Shipbuilding is a traditional make to order industry. In almost all cases, shipbuilders produce products following receipt of a customer order (that is, there is no building to stock). Since the price for ships is quite high, customers want the ability to customize the ship being ordered to fit company preferences, specific needs or requirements for the ship being ordered, or other reasons. Shipbuilders, however, seek to develop and maintain a productive manufacturing system. This means they must develop a production process that contains "repeatable" process flows. These repeatable flows provide the ability to plan and schedule production in a manner that emulates a continuous flow production process. Without the ability to develop a production process like this, shipbuilders would be designing and producing new products and production processes for each new ship. Since this would result in low productivity and high cost, the principles of mass customization have been employed. To understand this application, a review of the shipbuilding production process is required.

Shipbuilding is a hierarchical, assembly process. At the initial stage, the work involves parts manufacturing and component procurement. The existing world shipbuilding market currently possesses much more production capacity than the demand for new ships. Thus, a key aspect for the survival of any shipyard in the modern building business is being successful in the bidding process and winning contracts for shipbuilding, and doing so in a way that minimizes cost while improving chances for winning new contracts. This implies that the shipyard should have the skill to quickly and inexpensively prepare a contract design package and also have the ability to customize to owner requirements. The contract design package should contain production considerations tailored to the specific shipyard. Contract design packages need assessment and authorization by classification societies, regulatory bodies and government agencies. A complete procurement package is also an important part of the package for contract design. The shipyard that is bidding should be able to create correct and complete contract cost and pricing proposals to reduce risk, in case the shipyard wins the contract, and have the ability to assess acquisition and life-cycle costs, and investigate cost reduction proposals.

Shipyards considered as "world class" can provide prospective ship owners with fast, extremely detailed quotes and contract packages for requested design variations from their catalog of standard ship designs constructed and refined over a period of decades. Benchmarking data has shown that successful, "world class" commercial shipbuilders build an average of 10 ships (often each of a different design) per year. The best shipbuilders are successful in winning about one in ten bids. Thus, an average of about 100 contract designs and bids per year are required. While empirical data bases have been employed in many shipyards to achieve this design capability, a more formal design approach that permits electronic data exchange between design stages would be valuable. This will be especially important as experienced designers retire in the coming years.

Starting with a parent design, design rules and tools can be developed to permit rapid completion of a contract design and an associated cost estimate that can be used for bidding. The approach is based on developing functional volumes, such as cargo volume, engine room, deck house and bow, and then using parametric rules to resize these volumes to respond to customer requirements. The tools permit the use of first principles to validate the design and then seamlessly pass the design data to a cost estimating module. Thus a contract design can be quickly developed and analyzed. Assuming a successful bid, the design can then proceed seamlessly to greater levels of detail based on the volumes that were determined at the contract design stage. At this point, the detailed design within these volumes can proceed, within the bounds established at the earlier design stage. Here again, empirical approaches are most commonly employed.

Following acceptance of a bid, shipyards perform their detail design work (e.g. lines fairing, zone outfitting design) with the help of some industrial 3D design software. Very often the detailed design is started far ahead of the actual building process and will last until the ship is delivered. This design process should involve little change to most interim products. However, where customization of interim products is required to meet the needs of the customer, detail design and engineering work will be required.

3. High Level Mass Customization in Shipbuilding

The design and engineering approach uses a combination of existing interim product designs, including production processes associated with these interim products. Taken at its simplest form, this design approach is illustrated by the following Fig. 1 (Softley and Schiller, 2002)

Figure 1 shows that the design approach builds on a

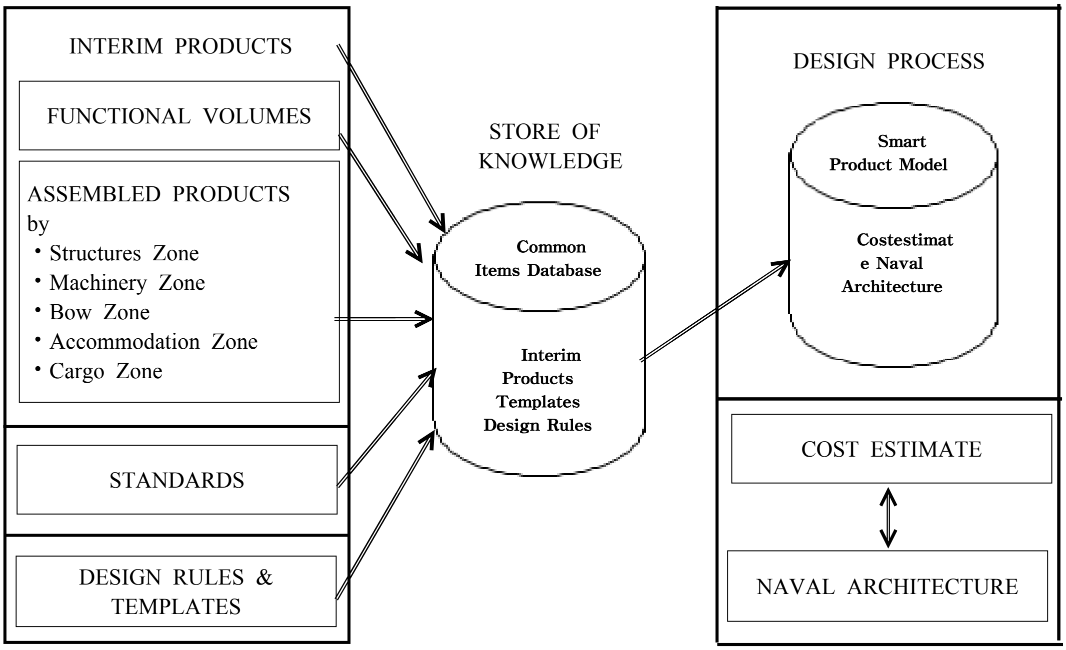

Fig. 1. CID and the Design Process

database of interim products and design rules called the Common Items Database. This is the starting point from which an actual ship design process begins. This database should contain the following information:

- A list of type-approved specification equipment with product data and the associated classification society certification for each item.
- A vendors' list and equipment identified for world class, non-specification marine material and equipment with product data.
- A vendors' list and equipment identification and supporting documentation for world class, non specification non-marine material and equipment with product data.
- Sets of nationally acceptable outfit material and design standards.
- Sets of nationally acceptable structural material and design standards.
- A set of metrics that characterizes the performance requirements for generic ship types, a set of design and cost estimating metrics and the whole ship design rules and guidelines for generic ship types.
- Generic interim products by zone and design and material templates and rules for interim products.
- Design and material templates and rules for ship structure, cargo areas, machinery areas and accommodation spaces.
- Portfolio of preliminary designs.

In summary the database contains all types of interim products as well as the design rules that allow the products to interact with each other. For example, the functional volumes in a typical accommodation zone include: living spaces, equipment, safety areas and equipment, access routes, service routes, structure, etc. Similarly we can define the functional volume components in the other zones.

Once designers have access to these data, in terms of a specific ship design project, based on the owner's technical mission requirements, specification and government and class rules, the designers can select an excellent

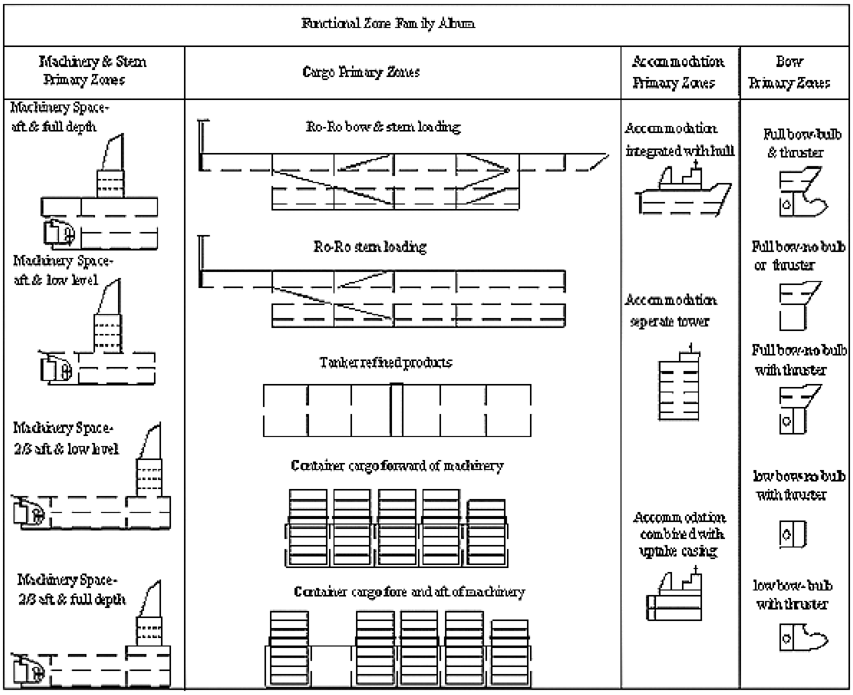

Fig. 2. Temple Design Process

parent ship from the database for reference. The design process begins with a major zone family album, from the database, made up of choices for the four major zones of bow, cargo, machinery space and accommodations. The following Fig. 2 (NSRP-ASE Project 99-21) shows the details of functional zone family album. This is a manifestation of mass customization in shipbuilding.

In each of the four primary zones, the designers will choose a specific zone level interim product that best suits the targeted vessel. The next job will be determining the required functional volume in the specific zone chosen. Let us take the main engine room as an example. Since the main engine and shaft system are usually specified in the owner's technical mission specification, the first step is to set the location of the main equipment items on the design template for the engine room according to specific functional rules. Thus the space can be defined for the primary functional layout of equipment. Also the envelope of preliminary functional space is sized to the maximum size of the major outfit assemblies. Next the designers will apply the secondary products from the database's interim products family album to the design template and from this they can define the transit routes for preliminary functional routing of services and spaces for the secondary functional layout of equipment. The envelopes of secondary functional equipment spaces are developed within the primary space boundaries.

Once the designers have finished functional arrangements, structural systems design, interim products design and production based system diagrams design in the four major zones, the next step is to assemble each primary zone into the ship and define it with the inter zonal design rules. The developed volumetric requirements are also passed on to an integrated naval architecture software suite, which refines the selected parent hull form and performs first principle naval architecture computations, including hydrostatics, stability, structures and powering. Once the hull form that satisfies the functional volume requirements is determined, accurate cost estimating is performed in the software suite utilizing the cost estimating data from the database.

It should be noted that system diagram templates and rule sets for each system (e.g. pipe, HVAC, electrical) that are sensitive to the performance requirements are also stored in the database. Based on the system diagram templates, standard outfit material, specified and non-specified equipment and interim products are selected from the database for the design of a specific marine system according to the design rule sets. Therefore, even in a product oriented design process, the systems design can be performed concurrently with the spatial or zone design process at the earliest stage.

The advantages the functional volume approach provides include:

- Reduces the risk that sufficient space is not available resulting in bad compromises being needed in detail design.
- Results in the ship that satisfies the needs of functionality and producibility.
- Creates design solutions which are intrinsically "high confidence and low risk".
- Reduces the overall cost and lead time of the current ship design.

4. Group Technology and Mass Customization in Shipbuilding

The principles of mass customization, when applied to shipbuilding, employ the concepts of group technology. Hyde defines group technology as "a technique for manufacturing small to medium lot size batches of parts of similar process, of somewhat dissimilar materials, geometry, and size, which are produced in a committed small cell of machines which have been grouped together physically, specifically tooled, and scheduled as a unit." (Hyde, 1981) In shipbuilding, the principle is used at the interim product or sub-assembly level to allow customization to fit specific owner requirements, without requiring a change in the basic production process or sequence. An example of how this can be utilized is shown in the following 2 figures. Fig. 3 shows a typical outfitting interim product, consisting of pumps, motors, piping and a manifold, all mounted on a structural frame. The first interim product contains 2 primary pumps with the associated motors, piping and structure.

Fig. 4 shows a similar interim product, following customization to increase the pumping capacity. That interim product has a third pump added. Despite that customization, the production of this customized interim product will not cause changes in the production process or sequence. It will require a relatively small increase in effort in design and production, however, to account for the extra pump. Similar kinds of customization can be applied to meet owner requirements. For example, one owner may desire to use pumps from a different supplier than the shipyard interim product standard. This customization uses the principles of mass customization because, here again, relatively small additional effort is required in design and production. This effort will not result in changes in the production process or sequence, and the benefits of learning curve improvements will still be apparent. This approach to design and production enables new ships to be customized to specific owner requirements, while reusing the basic design and production methods for interim products.

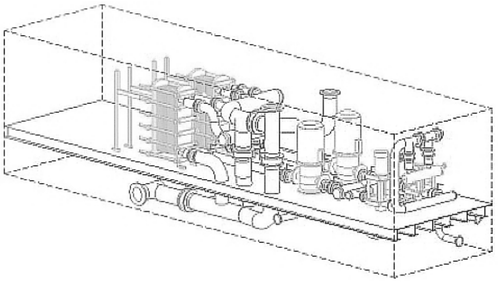

Fig. 3. Interim Product Example (Pumping unit for a given flow requirement)

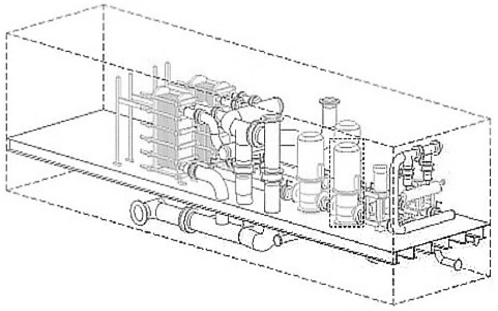

Fig. 4. Interim Product Example (Pumping unit parametrically redesigned to meet increased flow requirement)

5. Simulation Modeling of MC in Shipbuilding

Discrete event simulation is widely used as an enabler for the evaluation of production schedules, resource utilization, material and work flow, and capacity (Burnett et al. 2008). To study the impact of changes using mass customization principles on the production schedule in shipbuilding, a simulation model of a simplified and theoretical shipbuilding process is developed.

5.1 Shipbuilding production process and duration

A simplified version of the shipbuilding production process is presented in Fig. 5. This notional shipbuilding process is based on the schedule of the ship the PD-214, as it would have been constructed at Avondale Shipyards, Inc., New Orleans, Louisiana, in 1985 (Bunch 1995). Although this study represents a somewhat outdated production process, it provides a solid foundation for analysis of potential changes resulting from customization decisions. It is still one of the most comprehensive published shipbuilding production planning studies and is thus chosen as the basis for this simulation study.

For individual durations of shipbuilding activities, Monte Carlo simulation assumes the triangular distribution, Triangular (min, most likely, max). The min and max represent the minimum and maximum production times, respectively. For 'most likely', Avondale's standard completion time for the production process in Table 1 is used. Table 1 presents major production processes in the building of the notional ship (the PD-214) at Avondale Shipyards and their assumed distributions.

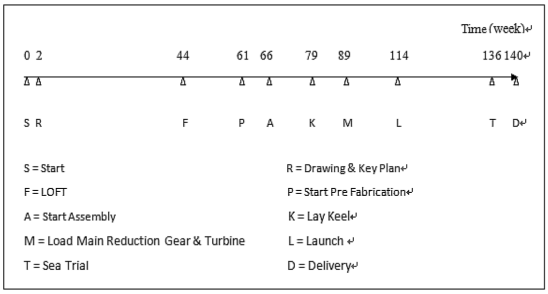

Fig. 5. Simplified Shipbuilding Production Process

Table 1. Major Production Durations and Their Distribution

Major Production Process	Standard completion time	Distribution
Preparation	2	Triangular(2,2,2)
Drawing and Key Plan	18	Triangular(16,18,20)
Principle items and steel ordering & other engineering	24	Triangular(22,24,26)
LOFT	17	Triangular(15,17,19)
Prefabrication	5	Triangular(4,5,6)
Assembly	13	Triangular(11,13,15)
Erection 1(from keel laying to shaft center sighting)	7	Triangular(6,7,8)
Erection 2(from shaft center sighting to loading main reduction gear and turbines)	3	Triangular(2,3,4)
Erection 3(from loading main reduction gear and turbines to loading funnel)	15	Triangular(13,15,17)
Erection 4(from loading funnel to loading rudder & propeller)	3	Triangular(2,3,4)
Erection 5(from loading rudder &propeller to loading deck crane)	3	Triangular(2,3,4)
Erection 6(from loading deck crane to launch)	4	Triangular(3,4,5)
Outfitting(from launch to sea trial)	24	Triangular(22,24,26)
Sea trial	4	Triangular(3,4,5)-

5.2 Learning curve impact on production time

Wright (1936) first developed the log 2-based learning curve to study the learning effect in a single production line. In predicting future process performance in a system where learning curve has an effect, Wright's log 2-based model still shows good results (for more detailed information about learning curve effects, see the description in Lu, 2008). Wright's learning curve model is given by the following mathematical model:

$$y_n = an^{-b} \tag{1}$$

Here y_n is the process time to complete the nth production unit, n is the cumulative number of units completed, a is the time needed to complete the 1st production unit, and b is a progress rate. The common method to determine progress rate is to take the logarithm of an improvement percentage (or curve rate) divided by log 2. In the learning curve model, it is usually assumed that production time achieves no further improvement after certain predetermined numbers of units have been produced.

In this experiment, it is assumed that the curve rate is 95% and there is no more improvement in production time when the accumulated production unit reaches 100. Avondale's shipbuilding data (from the PD-214 study) are used to estimate the value of a in equation (1). Thus, for the nth$(2 \le n \le 100)$ ship, the completion time y_n for individual production processes is obtained by

$$y_n = an^{-\log 0.95/\log 2} \tag{2}$$

Here a is the random production process time from Triangular(min, most likely, max). For $100 \le n$, the random production time can be easily obtained by plugging 100 into n in equation (2).

5.3 Assumed levels of customization in engineering and assembly

In the shipbuilding industry, traditionally customized products are made using production processes that cope well with a great variety of products and with design processes that can accommodate a high degree of customer involvement in specifying the products. A customized product is designed specifically to meet the needs of particular customers. Customer involvement at a specific point in the shipbuilding production process can have an impact on the ship delivery schedule by lengthening associated production times. For instance, a customization of the major propulsion system, such as a change of propulsion specification has an impact on design of the propulsion system and its production time.

This experiment will use a high level or master milestone schedule for design and production, and then assume duration changes for design and production of interim products. In shipbuilding production processes, the customization and its potential impact on delivery schedule mainly occurs at engineering and the assembly production stages. Avondale, like most shipbuilders, utilized the process lane concept in the production of ships. Following this approach to assembly, there are three general construction stages: pre-fabrication, sub-assembly and assembly. The relative level of effort for the full ship used in this example is about 1 hour of engineering effort for 10 hours of production effort. A reasonable assumption would then be that small changes in engineering to enable mass customization of interim products will produce production hour changes that are considerably larger than the amount of the engineering changes.

Customization in engineering affects the activity duration of drawing and key plan generation. Customization can be categorized into three distinct categories: small, medium, and large customizations. Changing the placement of small parts such as valves is an example of a small customization. The reason for this kind of customization is typically linked to the layout and piping of interim products, and if the layout is changed, the placement of parts may also be required to be changed. Depending on the specific situation, this kind of customization may increase the engineering duration up to approximately 2%. Since there is only a relatively small change in the interim product, the increase in work duration for assembly will be modest. We have assumed this low level of increase will be about 10%, based on the comparatively larger labor content in production compared to engineering.

When a customer wishes to use a different type of fuel, this type of customization may increase engineering time duration up to 8% depending on how much the new system deviates from the standard fuel system. We would consider this customization as in the medium category. Here the duration increase in engineering is assumed to be 8% and the production duration increase is assumed to be 20%. More significant customization can also occur, although less frequently than in the small and medium cases described above. For instance, when the customer wants to change the main engine, this may require changes in the overall fuel system and other sub-systems associated with the propulsion system. This kind of customization can increase the engineering period as much as 15% since this is basically a redesign of major components in the ship, which has impacts on the design of a number of sub-systems. In this case, production duration increases on the order of 30% are assumed. Thus, three different levels of 2%, 8%, and 15% are selected as design points in engineering customization and three different levels of 10%, 20% and 30% are selected for assembly customization. If the changes are too significant, the production process is also likely to change, and thus mass customization is not being employed. We assume that increased production effort greater than 30% would imply that new production processes would be developed and thus the application of mass customization is not possible.

Basically more customized production processes may need more completion time to accommodate a higher degree of customer involvement in specifying the interim products. However, depending on the situation, customization may or may not cause increases in production duration. To depict such a situation, the production time y_n in (2) increases proportionally with increased levels of customization, but its increase in duration occurs at random. The randomness of customization is realized by the generation of a random number (0, 1) and its multiplication by the customization level (percentage).

5.4 Simulation model for ship delivery scheduling

The major objective of this simulation experiment is to investigate the impact of customization changes on the shipbuilding completion schedule. A certain level of customization at engineering and assembly may cause production delay so that the final ship delivery may not meet the original delivery schedule. Thus, the expected on-time delivery ratio of ships to the contract will be an appropriate performance measure for evaluating the customization impact on delivery schedule.

To achieve this, a simplified shipbuilding production process is described by an AweSim network consisting of logical nodes and activities (durations) (Pritksker and O'Reilly, 2008; Storch, Lim and Kwon, 2011). Model description includes the following:

- Inter-contract times follow the exponential distribution with a mean of 30 weeks.
- The number of ships per a contract is 1, 2, 3, 4, or 5, respectively with equal probability of 0.2.
- Engineering time for multiple ships of the same type is the same as that for a single ship.
- Available number of docks at Avondale Shipyard is 4.
- Shipbuilding production activities have stochastic durations of Triangular distribution in Table 1 and learning effects realized by equation (2).
- For a contract to build the same type of multiple ships the delivery interval for consecutive 2 ships is assumed to be 12 weeks and the production schedules are adjusted to start 12 weeks later automatically.

6. Simulation Experiments and Results

A set of simulation experiments is conducted at the previously defined levels of customization in engineering and assembly. At specific customization levels in engineering and assembly, the simulation experiment consists of 10 independent replications. Each replication stops when 250 ships are built in the shipyard. Table 2 summarizes the average on-time delivery percentage at considered customization categories in engineering and assembly.

Table 2. Average On-time Delivery Percentage with Customization

Customization Category in Assembly	Customization Category in Engineering			
	None	Small	Medium	Large
None	64.4%	63.6%	62.2%	60.9%
Small	61.6%	61.5%	60.4%	58.4%
Medium	58.6%	58.4%	56.9%	54.9%
Large	53.8%	53.5%	51.6%	50.2%

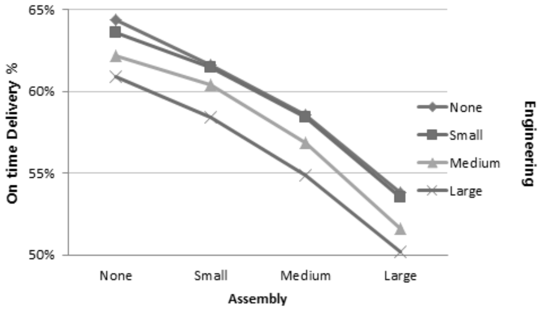

Fig. 6. On-time Delivery Percentage with Customization Category

Without customization in both engineering and assembly, average on-time delivery percentage is 64.4% According to Avondale's shipbuilding schedule for the PD-214, the construction period from contract to delivery is 140 weeks. The simulation result for the construction period shows it is about 10 weeks longer than Avondale's deterministic schedule of 140 weeks. This may be due to the stochastic shipbuilding durations, assumed inter-contract arrival process and Avondale's shipbuilding dock capacity.

As expected, the higher amount of customization in either engineering or assembly reduces on-time delivery percentage. For instance, in the case that the customization category of both engineering and assembly are large, the on-time delivery percentage decreases by around 14%. With respect to three categorized customization levels of small, medium and large, the effect of assembly customization on on-time delivery percentage is greater than that of engineering. When there is no customization in engineering, assembly customization of 'small' decreases the on-time delivery percentage by 2.8%, which is more than 0.8% obtained by 'small' engineering customization with no assembly customization (see Table 2).

For a specific customization category of engineering, the assembly customization effect is presented in Figure 6. As the customization levels of assembly increase, the on-time delivery percentages decrease in similar shape of curves for three categories of engineering customization.

7. Conclusions

Mass customization permits changes in the product to meet specific customer requirements without substantially impacting the cost or delivery schedule and without requiring a change in the basic production process or sequence. In shipbuilding, the principles of mass customization can be realized by employing the concepts of group technology on the interim product or subassembly level. This approach is made effective by the support of the functional volume approach with parametric design rules. This paper has described how mass customization can be implemented in shipbuilding. To date, no studies have specifically presented this concept. The approach outlined here can be expanded for implementation in other large assembly manufacturing industries, such as commercial airplane production, large land based construction and offshore oil and gas production facilities.

In this study, a simulation model of a simplified and theoretical shipbuilding process based on a notional shipbuilding project of the ship PD-214 is developed to evaluate the impacts of various levels of customization in engineering and assembly on delivery schedule. In conducting simulation, stochastic production times were assumed and the effect of learning curve improvements was considered. The results of the simulation experiment show how on-time delivery percentage is decreasing as customization change increases. It also showed that as a result of the continued learning curve improvements, the degradation of on-time delivery performance was less than 15% (for large customization in engineering and production). Thus, the benefits of employing mass customization for large assembly industries seem apparent.

It should not be too difficult to apply the approach and results of this study to real shipbuilding practices. The shipbuilding process simulation model could be adjusted to a more suitable (though much more detailed and complicated) one in order to better reflect specific shipyard characteristics. Based on the process, the impacts of timing and amount of customization on production performance and delivery would be evaluated using actual shipbuilding data, which would enable the shipbuilder to be well prepared for effective planning and scheduling and even for a quick and proper response to specific owner requirements presented at the contract design stage.

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