Research Article

A systematic approach of lean supply chain management in shipbuilding

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Received: 7 October 2020 / Accepted: 7 April 2021
Published online: 21 April 2021

Abstract

This paper presents a systematic approach for lean supply chain management in shipbuilding industry based on analysis of the unique characters and processes of shipbuilding. The approach constantly improves productivity and retains low costs. The system that covers seven sub-systems on three different levels is created based on the lean thinking and supply chain management theory. In the lean supply chain management procedure, the operational data of the shipyard and suppliers are timely collected, monitored, and analyzed, and weaknesses in the supply chain are identified through performance measurement to suggest improvements. With this approach the entire shipbuilding supply chain can be continuously optimized and controlled. This approach is concluded and proofed functional with actual operation in a leading shipyard in China, Shanghai Waigaoqiao Shipbuilding Company, guided by Shipbuilding Modeling 2.0 Program of China state shipbuilding corporation.

Highlights

- To the best of the authors' knowledge, they are the first to present a systematic theory based framework, operational method, and recirculation approach for optimizing lean supply chain management (LSCM) in shipbuilding. Although the theory of LSCM has reached into a very mature stage in some traditional industry, but it is still a greenfield in shipbuilding.
- Most experts and professionals in shipbuilding industry would like to consider the production of ships and offshore products as a project due to its nature of unique and single. But the basic theory and tool of LSCM can still functioning after abstract the characters and processes, and then lead the practice and study of LSCM in shipbuilding to improve the efficiency and effectiveness of shipbuilding.
- The authors are shipbuilding and supply chain management experts from Waigaoqiao Shipbuilding Company (SWS), which is a leading shipyard in China. Because of their theory and practice based knowledge, they can easily identify the key problems of shipbuilding operation and have first-hand access to worldwide shipbuilding performance data. In addition, the authors have experienced the great transition and reform from traditional to lean shipbuilding.

Keywords LSCM · Shipbuilding · Inventory · Performance measurement

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1 Introduction

Lean thinking is about determining how to deliver more value to society, individuals, and the environment; more specifically, the methodology includes determining how to align with value-creating actions in the best possible way, perform activities without interruption whenever someone requests them, and perform them more and more effectively [1]. Lean Principles and Practices claim to create value for customer with growth in every type of organization in which they are implemented [2].Lean supply chain originate from the just-in-time philosophy, which was first adopted by many American and European firms in the late 1980s and applied at Toyota's Takaoka facility [1, 3]. Since then, lean supply chain management (LSCM) has played a crucial role and reached a matured stage with the development of new IT technologies in most manufacturing industries such as the automobile, electronical communication, and aviation [4].

Although shipbuilding technology differs from that applied in, for example, automotive products [5] and can be considered in many aspects similar to construction technology in which the product is place-bound and the site itself is a resource [6]. The processes and working flow differ from those of most manufacturing methods studied in both LSCM and supply chain management (SCM). According to Aslesen and Sigmud [7], "The available literature on implementation of lean in shipbuilding environment is quite restricted due to novelty and the restriction of the concept. Lean shipbuilding is very specialized one and its application is considered to be one of the extensions beyond lean construction". Nevertheless to say, the SCM for shipbuilding can be summarized and simplified by analyzing the shipbuilding characteristics.

Leading shipyards such as Kawasaki in Japan and Daewoo in Korea implement lean shipbuilding by successfully applying lean principles and total quality management. SCM is essential for improving the efficiency of shipyards in the I4.0 technologies [8, 9] and lean manufacturing; how to combine SCM and lean manufacturing to improve the efficiency of shipbuilding has become increasingly important.

SCM in the leading shipyard of China [i.e. Shanghai Waigaoqiao Shipbuilding Company (SWS)] is part of the lean-thinking-based of Shipbuilding Modeling 2.0 Program [10] of the China State Shipbuilding Corporation (CSSC). The program has improved the building efficiency and business performance of the company. The LSCM system presented in this paper represents the worldwide shipbuilding development in leading shipyards and is based on shipbuilding experts' knowledge.

The following sections of this paper presents a background analysis of the SCM characteristics in shipbuilding, lists the difference between this and other industries, and explains why LSCM has been chosen for shipbuilding and how this unique method can be implemented. Based on these factors, a systematic approach for LSCM implementation and pursue perfection with lean thinking and endless circulation is presented. Finally, the key points and important problems of this study are discussed, and its contributions are summarized.

2 Characteristics of SCM for shipbuilding

One of the major differences between shipbuilding and most other manufacturing is that the ship or the offshore product is designed, developed, and built during the project development stage instead of being ready before the production. In mature manufacturing processes, the material, technical details, type, suppliers, and components are selected during the design stage; thus, the new design product is trial-manufactured and tested before the actual production [11]. Shipbuilding does not include such trial manufacture and, is therefore similar to construction projects [6]. The shipbuilding industry is largely characterized by the application of project-based approaches for the building of ships, offshore products, submarines, and their repair and overhaul [12].

Saved for the requirement from the client, the shipbuilding project normally starts from the basic design stage compared with the complex final product. The basic design briefly specifies the major technical scope, performance, function, and systematic working method. Subsequently, the shipyard signs the contract with the client [11]. The shipyard normally produces and delivers the ship within approximately two years (the processes includes detail design, engineering, procurement, construction, and test and trial).

2.1 Short supply chain

Figures 1 [13, 14] and 2 compare the general supply chain with that of the shipbuilding industry; the latter is typically shorter because it does not contain the distribution of products to the customer; the supply chain ends with the completion of the project. For example, the SCM processes for a floating production storage and offloading unit (FPSO) (which is used in the offshore oil and gas industry for the production and processing of hydrocarbons and for the storage of oil) for a certain client includes managing a series of activities along the supply chain. Finally, all materials and components (e.g. steel plate, outfitting, cable, piping, machinery, etc.) from the suppliers must be delivered to the correct place of the yard at the correct time with the correct price; in addition, the quality of products must meet the requirements of the building process in the shipyard. All these factors are not included in the management plan for the delivery of FPSO unit to the client. The shipyard functions as a turnkey contractor that delivers the final product directly to the end-user or owner [15] when all scopes in the contract have been met.

2.2 Low standardization ratio (LSR)

Compared to those of other industrial manufacturing processes, the standardization ratio of the raw material and intermediate components in shipbuilding is rather low [16].

First, the ratio is determined by high degree of customization instead of standardization. Except yachts and some small ships less than 5,000 tons deadweight, most ship types are not mass-produced. The number of vessels with identical designs that are simultaneously or continually constructed doesn't exceed 10 vessels in all the major shipyards worldwide.

Second, the degree of standardization of raw material is very low. The key raw material for shipbuilding is the steel including the steel plates and profile bars, thereby representing approximate 30% of the total cost of shipbuilding. Owing to the development of lean production designs, the three dimensional modelling has been used to simulate all structures, equipment, fittings, and major intermediate components with computer model before construction. To increase the use and reduce the cost and lightweight of the ship to allow the owner to carry more cargo, the designers determine the optimal steel grade and thickness for each structure; subsequently, the exact demands of steel plates and profile bars are defined. For example, the 5500 types of steel plates (which correspond to 14,000 steel plates) for the construction of an FPSO unit in the SWS approximately 70 thousand tons.

Furthermore, the suppliers of the outfitting for piping, passageway, equipment installation, and cable way fabricate them according to the production drawings of the shipyard. The shipbuilding industry committee and per shipyard have established a set of standard for almost all fittings; however the standard set does not support the standardized production owing to the great number of types and uncertainty regarding the quantity, size, and arrival date of each fitting type.

The key machinery for the propulsion, anchor, power supply, and navigation can be standardized, however the shipyard and ship owner still have customized requirements in the signed technical agreement. The equipment is normally shop tested with witness of the Class (i.e. a professional party on behalf of the flag government and other authorities), representatives of the yard and owner before the dispatch; the installation is followed by commissioning, docking and sea trial.

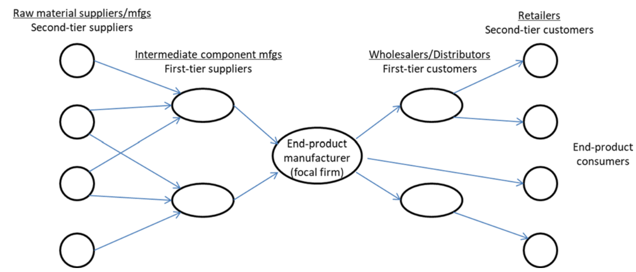

Fig. 1 Generic supply chain

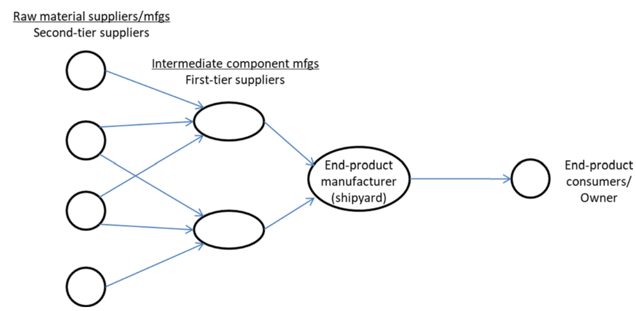

Fig. 2 Shipbuilding supply chain

Based on the analysis above and estimation of several typical shipbuilding projects, the manufacture ratio of standardized raw material and intermediate components is approximately 20%; and the weight of standard material and components is only approximately 5% of the ship. This leads to problems when material of the inventory must be replaced in the event of a failure along the supply chain.

2.3 Complexity

Shipbuilding has the peculiarity that the different locations in which each of the parts is made belongs to the same manufacturing center; nevertheless, the locations are distributed over a large area, which complicates the processes [17].

By nature, shipbuilding projects are huge projects with substantial jobs, a large numbers of products, and a series of processes involved. For example, a FPSO unit construction structure can be broken down at least 5 layers to achieve the completion of the project as shown in the Fig. 3. There are approximately 1000 kinds of raw material and products to purchase in order to complete 50 thousand pieces of components and finally assembly into the FPSO unit. Based on when the section, blocks, meg-blocks purposed to be ready, these material and products engaged in the sections, blocks, and meg blocks or directly mounted onboard are requested to arrive at the Yard in the correct time according to building schedule [11].

The machinery, components, fittings, and raw materials are produced by a great number of suppliers at different location and have different size, and typologies [8]. Thus, the supply and delivery must be coordinated according to the technical specifications, test requirements, cost, quantity, delivery standard, and schedule.

2.4 Uncertainty

Because trial-manufacturing is not existent in this field, shipbuilding supply chain has in an enormous degree of uncertainty. Although predicting the exact required quantity, size, grade, and even characteristics of the material and products at the early project state is challenging, the shipyard must prepare contracts with the suppliers and determine the required resource to ensure that supply plan meets the building schedule [11]. For example, most fittings including the ladders, pipes, valves, and cables only can be defined during the detail design stage and be precise predicted the demand in production engineering stage; therefore, it is almost impossible to order the right amount of material at the start of the project.

Uncertainty and unexpected changes can also be introduced by the related stakeholders [11]. The following list presents a few examples:

- Technical specification Change Order comes from the client;
- Safety rules can be changed caused by the force of related authorities and international organization;
- Technical updates made by the suppliers can lead to unforeseen modification;
- The building schedule can be adjusted owing to changes regarding the human resource, force majeure, and unpredictable technical challenge.

3 Analysis of LSCM in shipbuilding

A common practice has been to carry a higher level of inventory to compensate for greater uncertainty [3]. But it doesn't work in SCM of shipbuilding owing to the LSR and complexity. To some extent, the inventory of raw material and intermediate component in shipbuilding is not real a buffer between manufacturing and order fulfillment. Inventory that is not in line with LSCM results in an inefficient and ineffective process flow. A safety stock of non-standard raw materials and intermediate components increases the waiting time and does not prevent the supply failure. For example, the steel fitting for block 642 cannot be swapped with the one for block 641; in addition, the DH32 steel plate (12 mm thickness and 12,000 × 2600 mm size) cannot replace the DH32 plate with 12 mm thickness and a different size.

Thus, LSCM is the optimal choice for shipbuilding supply chain [17]. The principles on which the lean philosophy

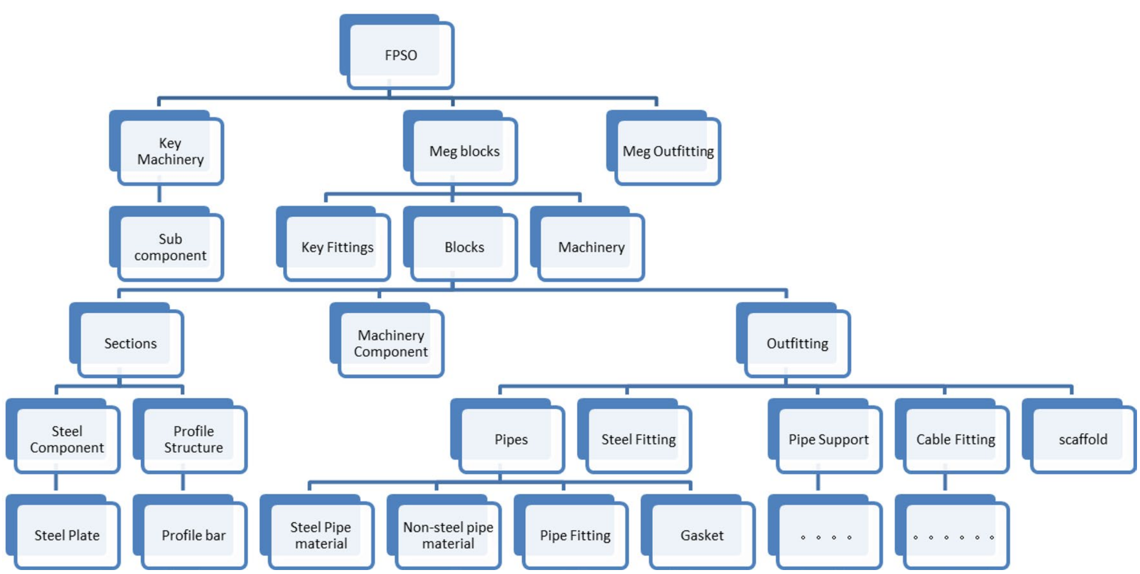

Fig. 3 Structure of shipbuilding construction

is based on and its practices, make them ideal for the supply chain [8] of shipbuilding.

3.1 Intermediate products of SCM in shipbuilding

Similar to the philosophy of to create modular structures, each functional part operates at a certain degree of independence from the rest [18]. In the advanced shipbuilding practice that deals with the complexity and LSR, a certain part of a proper building stage is defined as an intermediate product. The scope of the intermediate products is designed into a systematic structure that coverings all necessary management elements during shipbuilding (e.g. the blocks, meg-blocks, half ship of the hull part, building components of a module, fitting units, pallets, key machinery); in addition, the intermediate product can represent as a package of job as design, manufacturing, or purchasing [10].

The same category of or similar intermediate products are recognized, designated, organized according to the shipbuilding processes. The shipbuilding production facilities and procedures are integrated into a flexible production line by organizing these activities of the basic element for intermediate products from design, fabrication, and management in the digital way as hull block building, outfitting and pipes for each block. According to the detailed map in Fig. 4 and paragraph of about the plan of LSCM in shipbuilding, the block is a typical intermediate product in shipbuilding.

Under these conditions, the SCM consists of a group SCMs for the intermediate products which are simpler and have a higher standardization ratio. For example, one machinery purchaser only coordinates 30 engines, 30 shipsets of purifiers, and maybe some other key machines if the shipyard builds 30 ships in one year; the person(s) in charge of steel fittings is responsible for planning, contracting (with, for example, seven factories), and ensuring that the production of approximately 9000 pallets of steel fittings for these ships meets the shipbuilding schedule.

Each intermediate product is coded and named hierarchically in hull number, category, installation stage, pallet number, and serial number. It can be traced and managed for the whole life in the enterprise resource planning (ERP) system (from the design, purchase, inspection status, check-in and check-out in the warehouse, and onboard installation).

3.2 Quality control of LSCM in shipbuilding

The key aspect of quality control in LSCM is to ensure that no defective product enters the production line and the production flows without mistakes or defects [1]. A defective product found in the production line or even a later stage of shipbuilding will cause a delay and increase the cost owing to the LSR and complexity. For instance, in one shipyard of China, one platform supply vessel had to been returned to a dry dock; the structure was cut in the aft body and the thruster was dismounted for inspection owing to the leakage during the sea trial of the ship. This additional repair caused a loss of approximately one million RMB and delayed the delivery of the ship for nearly one month. Even the discovery of a pallet of steel fitting with galvanized defects during check-in inspection delayed the production of the block for at least one week; such event may delay the entire shipbuilding schedule if the block is on the critical path.

For a continuous building process without interruption caused by quality problems of the supplied products, all defective products must be identified and repaired/ replaced before the check-in in the warehouse because there is no backup inventory of raw materials or intermediate components [19]. According to Deming, we should seek the best quality and work to achieve it with a single or a few key supplier(s) for and one item in a long-tern relationship [20].Therefore, a completed supply chain monitoring system should be established for SCM, which covers the selection of the supplier, contract management, production report of the maker, factory acceptance test or check-in inspection, and performance measurement of the suppliers.

3.3 Plan of LSCM in shipbuilding

The plan system defines the detailed schedule for design, engineering, procurement, construction, and commissioning of the shipbuilding projects. The project schedule based on the mile stone plan is developed and refined with the work breakdown structure [21] and based on the required duration of each step by aligning the critical path of the building process [11]. In shipbuilding, the design department of the shipyard firstly carries out the blocks and meg-blocks division as shown in Fig. 4; this step can be considered as work breakdown step in ship construction. Each block is an intermediate product of the shipbuilding process.

During the designed shipbuilding process, the sequence of meg-blocks (which consist of several blocks) are erected and assembled to build a ship in the dry dock. The machinery, outfitting, key components, and raw materials for hull structure, pipes, outfitting must arrive at the shipyard warehouse and mounted onboard within the scheduled time frame. For the successful coordination of the construction steps, the shipyard must clear communicate the lead time of the machinery, outfitting, and

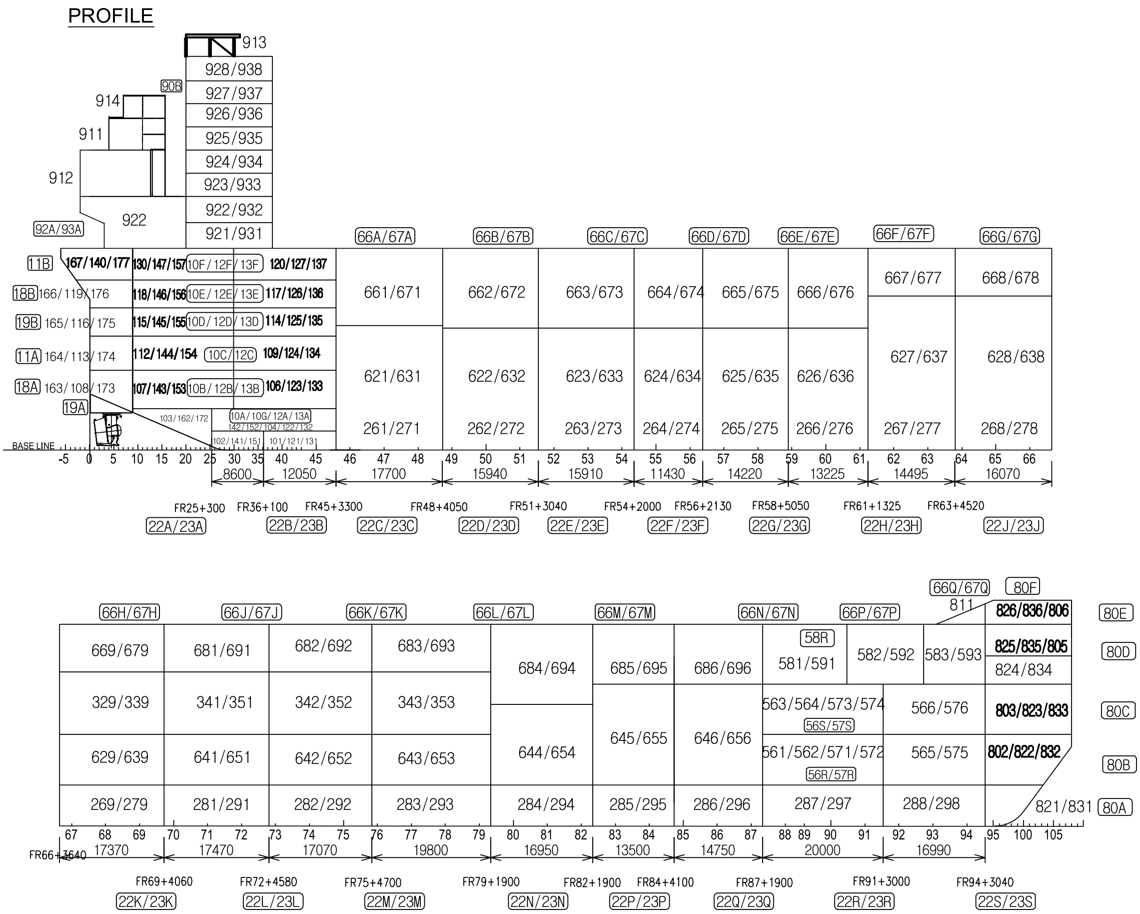

Fig. 4 Block division plan

materials in advance. Thus, the delivery plans must be prepared during the design stage.

These plans are the most important factor in the LSCM system. The correctness and preciseness have a significant influence on the operation of LSCM and production. Poor plan can result in poor performance measurement index; in particular, they can affect the efficiency group.

3.4 Performance measurement of LSCM in shipbuilding

Such as in most measurement and evaluation solution for the performance of SCM in other industries, the measures of the SCM in shipbuilding still fall into two broad categories: Effectiveness and Efficiency [3, 22]. The key point is how to build a systematic approach to monitor and refine the effectiveness and efficiency of LSCM in shipbuilding.

Each leading shipyard establishes its own standards to measure the basic performance of its supply chain; the approach assesses the schedule matching performance, cost, quality, and service. The most important facilities in a shipyard are the dock and outfitting wharf; thus, the production process in line with the building schedule to maintain the highest degree efficiency of the dock and wharf is the key and nuclear effectiveness of SCM in shipbuilding.

The efficiency performance in the LSCM process is assessed based on the inventory size. As already mentioned, there is almost no backup inventory in shipbuilding; nevertheless, more inventory or more waiting time is considered to compensate for poor product on quality and delay caused by the suppliers. For example, the products of categories B and C (see the Strategic Policy in Sect. 4.1) are inspected when they arrived at warehouse of the shipyard. The shipyard includes a few days or even a couple of weeks of buffer time for the arrival of the material and equipment to compensate for possible delays and defects. Thus, the inventory size depends on many aspects such as the quality control, plan execution, and risk management. Evidently, a smaller inventory reduces the total cost of SCM in shipbuilding.

4 Systematic approach of LSCM in shipbuilding

With the study and optimization guided by CSSC Shipbuilding Modeling 2.0, the improvement of shipbuilding processes are driven by the increasing of efficiency of production flow and reducing of total cost. Therefore, SCM is an important part to support the lean production in shipbuilding.

In the beginning, the shipyard considers the supply chain as the support and preparation of the lean production; it is pushed by the shipbuilding processes. With the study of SCM theory, the management principles can be integrated with the shipbuilding supply chain.

Based on the experience of the authors who work in the SWS, the LSCM plan is established based on seven sub-systems to integrate all detailed procedures (Fig. 5) in three levels; the first called as foundation level constitute the foundation of the management principles, the execution level includes the operation guidelines, and the index level represents the performance measurement.

4.1 Foundation level of LSCM in shipbuilding

In the coding system, all raw material, intermediate products, and pallets are systematic named and coded according to category, fabrication method, and installation stage; the codes, which consist of numbers and letters, are used for the entire product life cycle: from their design, purchase, check-in and out at the warehouse, production planning, installation, and inspection. The coding system (i.e. basic language of LSCM in shipbuilding) [10] is combined with the ERP system of the company and other software. Thus, digital tools can be used to control the way procurement teams work [23].

In the strategic policy, the supply commodities are classified into four categories according to the complexity and value [24]: critical, bottleneck, leverage, or routine [3]. Subsequently, the detailed management principles of the different categories are implemented. Moreover, the critical commodities are subdivided into three detail categories as A, B, and C; in addition, the suppliers of bottleneck commodities are classified into three levels to express the different degrees of importance in the production chain. Category A includes critical machinery with the highest complexity and value, category B includes other independent product with lower importance, and category C includes raw material and rest fittings. The suppliers of category A are normally reliable partners of the shipyard. The designers of the shipyard usually discuss all technical detail of all commodities of category A and non-standardized items of category B beforehand. In addition, the manufacture of these products in the suppliers' shop is carefully monitored before the delivery. The shipyard also put different frequency and concentration on the monitoring of different level's suppliers of bottleneck items; normally, they coordinate with the suppliers of the first level on the weekly basis.

Pallet management is a common practice in shipbuilding [10]; one batch of fittings of the same kind is installed at a certain step; because this batch can be included in the one work order, it is called a pallet; it is normally put on a pallet during flowing in the production but sometime is not. The pallet is the smallest unit of the intermediate products; all the raw materials and fittings can be organized into pallets with specific codes to realize lean design and production.

4.2 Execution level of LSCM in shipbuilding

Lean plan management is the most important basis of LSCM in shipbuilding; it allows all stakeholders to work

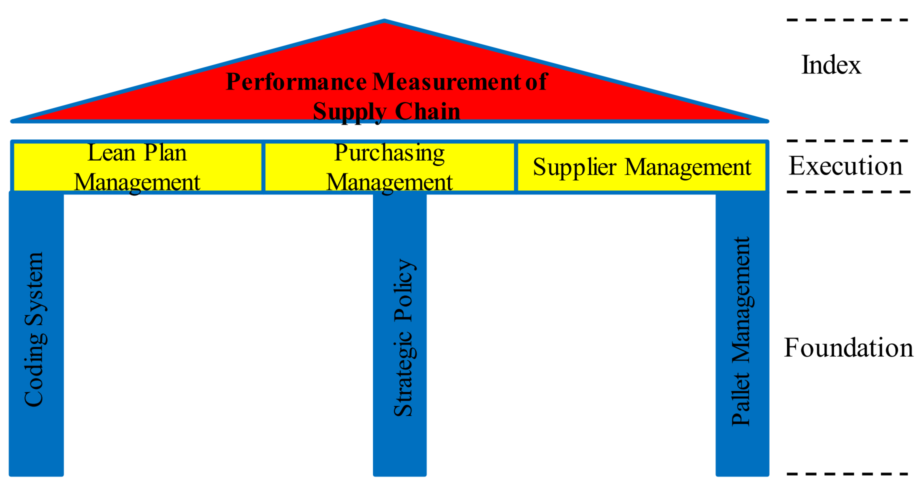

Fig.5 Frame of LSCM for shipbuilding

together according to a coordination plan [25]. The plan includes the drawing delivery plan, schedule of the raw material, fittings, and machinery. In addition, it is well aligned with the production plan for all intermediate products from different working departments [10]. The set of plans must be balanced according to work load and facilities of the shipyard, and officially published when the shipbuilding project starts. The plan includes uncertainty that can be caused owing to marketing problems and force majeure. In these situations, the plan must be re-evaluated and adjusted. Shipyards try to manage project plans in the make-to-order mode and, simultaneously control their production process in a the pull way according to the lean manufacturing principles [26].

Purchasing Management is the basic and main work of the SCM team. To realize a successful SCM process, the shipyard must establish a set of processes to monitor all the procedures, from the selection of the suppliers, to the price decision, commodity confirmation, and payment. This way, the shipyard managers can control the budget, cost, and risks.

The supplier management includes a set of procedure for the management of suppliers from the entering, performance measurement, communication, and elimination. The suppliers can be classified into different groups and taken different method on production report, communication frequency, and competition advantage according to the products they provided and the result of performance measurement. All kind of cooperation provides opportunities to the suppliers to grow and improve continuously together with the shipyard [3].

4.3 Index level of LSCM in shipbuilding

In the performance measurement stage, a detailed index system is established to evaluate the effectiveness and efficiency of the SCM [3].

All steps involved in the SCM belong to the production preparation. The objective of production preparation is the continuous production, which is defined by the building plan system. Continuous production means that the supply chain is effective. In summary, the supply chain ensures that high-quality materials and components (including steel plate, outfitting, cable, piping, and machinery) are transported to the right place of the yard at the right time.

The efficiency parameter represents the input of resources with respect to the performance output and production demand [3]. For shipyards, a smaller inventory benefits value flow in the production.

Some industries use balanced scorecard control method to measure their supply chain performance, for example automobile supply chain performance [27]. Effectiveness and efficiency index of in shipbuilding must be established to monitor and measure the key performance of supply chain in the shipbuilding.

According to the value calculation and total cost results in the SWS, the effectiveness shall be prior to efficiency in the two dimensions of performance measurement for the LSCM in shipbuilding. The modeling for performance measurement shall be calculated with the efficiency index based on the health of effectiveness shown briefly as below,

The key goal of LSCM is that all demanded high-quality materials, components, and intermediate products arrive at the production line on time; the measurement results are represented by the parameters V1 and V2 respectively. Service failure and defects that are found after the check-in inspection will have a negative influence on the production; these negative impacts are represented by the parameters V3, V4, and V5.

Most shipyards worldwide have similar measurement index defined in group V for the effectiveness of their supply chain. If there is only effectiveness index for the performance measurement; for satisfying the production, the managers will require the commodity to arrive earlier as a safety margin; therefore, the redundant inventory will result in increasing cost, reducing efficiency, and potential quality risk owing to the corrosion(some steel material is stowed at exposed warehouse); thus, the measurement of inventory is required to restrict superfluous effectiveness and other efficiency index is implemented.

However, the calculation of the efficiency as defined in group C differs depending on the balance of between the resource and supply chain condition of the shipyard. The values Table 1 are assessed and optimized based on the facility and supply chain in the SWS, which are advance among shipyards in China. Some shipyards in Japan and Korea have a better performance derived from their strategy with supplier and building efficiency. For example, the C1, inventory cycle of steel plate can be achieved approximately 25 days in Kawasaki shipyard in Dalian, which derives the precise supply from the steel supplier in Japan. Alternatively, the C1 value can reach 70 days in some small shipyards in China.

The weight factor of efficiency measurement in Group C can be adjusted according to the degree of importance and the supply chain condition of the shipyard. For example, shipyard can increase the weight of C3, plan match ratio of checkout for production if it wants to push the lean plan of the production. A high plan match ratio of checkout in supply chain must derive from a precise production plan. Supply chain managers will force the production managers to improve if the C3 index is poor.

4.4 Recirculation for perfection

The LSCM procedure can be executed step by step, as shown in Fig. 6. First, a set of management steps including the already presented seven sub-systems is prepared to specify the management principles and detailed procedure; subsequently, the colleagues are trained such that they understand and master the plan. The performance data are collected during the LSCM process when the entire system operates. Based on the performance data, the performance measurement model is built and analysed.

Recirculation in the presented system works in two distinct ways: it improves the index on the incremental path, particularly the Group C parameters. Afterwards, when the root cause for the poor performance has been identified, it is eliminated on the radical path to improve and refine the system [28].

However, to implement effectively radical and incremental improvements [1] of LSCM in shipbuilding, all the activities should be part of value analysis on lean principles of the building processes. Any local progress that harms the value stream of shipbuilding is not successful and recommended.

5 Discussion

Starting with the study of the LSCM in shipbuilding, experts suggest to approach [8] and achieve [17]a sustainable supply chain under the theory of I4.0. Suresh Sharma and Pankaj J. Gandhi raised a hypothesis to prove the efficiency improvement of shipbuilding by implementing lean principles and practices [5]. Other reports provided information on the digital transformation [12] and IT support for the efficiency improvement in shipbuilding supply chain. Moreover, Yu Hu and Lei Jiang studied LSCM in shipbuilding and reviewed successful practices in the industry [29], and give proposals for shipyards in a theoretic way.

The same author, Niansheng Chu, preliminary studied the character of SCM in shipbuilding and emphasized the coordination of design, purchasing, construction, and commissioning [11].The further study guided by lean thinking and systematic conclusion of operation is after that article published and more achievement in the systematic approach of LSCM is obtained.

As a research of LSCM in the shipbuilding enterprise finished by Yu Hu, it represented much work focus on SCM, Lean, LSCM, systematic process, methodology, achievement, and management system respectively [29]; however, the implementation of Lean principles in shipbuilding [5], in particular, systematic LSCM for the transformation of traditional shipbuilding supply chain into supply chain based on LSCM has not thoroughly been investigated. This study focus on LSCM implementation based on real operation of the SWS; the presented systematic approach includes detailed management principles and radical and incremental improvements.

There are different methods for measuring the performance characteristics of supply chain in shipbuilding [8, 29], nevertheless, the most successful method is determining the effectiveness and efficiency according to the research results and experience of the authors.

The digital revolution affects the supply chain in shipbuilding. As stated by Morgan Swink and Nada Sanders, a

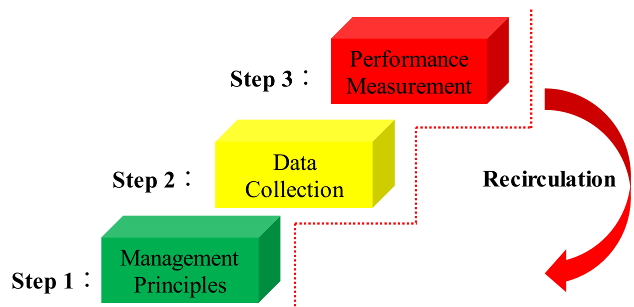

Fig. 6 Execution of LSCM for shipbuilding

Table 1 Index of LSCM for Shipbuilding

Category	Index	Mean rating	Weight
Effectiveness	Plan match ratio of arrival V1	> 98%	Health index
	Quality: passing rate of first inspection V2	> 95%	
	Claim of service V3	0 times	
	Liquidate damage V4	0 times	
	Safety conformity V5	Yes	
Efficiency	Inventory cycle of steel plate C1	55 days	0.30
	Monthly turnover of fitting pallet C2	3	0.25
	Plan match ratio of checkout for production C3	85%	0.25
	Yearly Cost reduction C4	3%	0.20
	Management improvement conformity C5	Yes	Bonus point

digital supply chain integrates technologies that automate and illuminate all processes including data capture, communication, analyses, decision-making, transactions, and transformations [30]. The ERP system of a shipyard enables supply chain to get technical data directly from the design model, and to execute the order management, inspection, payment, and measurement.

6 Conclusion

This article focuses on the key problems in shipbuilding supply chain and defines the LSCM frame and radical and incremental improvement paths for optimization. This paper is the first to determine the characteristics of the supply chain in shipbuilding, present the differences between LSCM from traditional SCM, and provide a systematical LSCM plan. Based on this information, shipyards can improve the efficiency of their shipbuilding supply chain.

Lean SCM (LSCM) plays an important role in lean shipbuilding management; LSCM and guidance regarding the plan, budget, working procedure, and working standard can be combined to establish a virtual production line running on the completed and quantitative management system integrated with informational network [10]. In the virtual production line, all intermediate products must contribute to a balanced and optimized flow among processes. The goal is timely, continuous, and reliable shipbuilding in the shipyard.

In the future, an index system for the performance measurement will be developed based on IT technology, specialized software, and the ERP system of the company (SWS). As mentioned in the book Three-Body Intelligence Revolution, the system can be designed and applied after the operation procedure has been fixed and the business model is mature [31].

In the first phase, an LSCM system with self-growing power will be established based on the information of this study. In the second phase, a more effectiveness and efficiency LSCM for shipbuilding will be established based on industrial Internet of Things, 5G technology, serverless architectures or block-chain technology, and artificial intelligence [23].

Author contributions Niansheng Chu is the leading author who conceptualized and wrote the paper; Xiang Nie and Jiang Xu implemented the lean production principles and established the performance measurement index; Kunlin Li managed the procedure and collected and analyzed the relevant data.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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