RESEARCH REPORT

MEGASHIPS IN MARINE TRANSPORTATION: A CRITICAL LITERATURE REVIEW AND EXTENSIONS

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ABSTRACT

Over the last few decades the size of container vessels deployed by liner shipping companies have significantly increased. In 2014-2015 three megaships with over 19,000 TEU capacity have been launched. Large vessels are more advantageous for liner shipping companies, as they provide lower voyage cost per TEU as compared to medium and small size vessels. However, some experts underline that megaships have an excessive capacity and cause negative externalities for other supply chain players. This study performs a detailed overview of scientific literature related to megaships in marine transportation. The collected papers are classified by different topics. Based on the literature review findings, necessary conclusions and future research directions are presented.

INTRODUCTION

Over the last 50 years the vessel size increased by 1,200% (*1*) from a maximum vessel capacity of 1,530 TEUs in 1968 to more than 19,000 TEUs capacity today (with some estimates for the next generation of container vessels reaching 24,000 TEUs). Large size vessels (a.k.a. megaships) may be more advantageous for liner shipping companies primarily due to their economies of scale, emissions reduction, and reduction in fuel consumption (*2*). However, when estimating total cost savings, it is necessary to account for port congestion, equipment costs, administrative costs, etc. (*3-5*). If all these cost components are considered, the total savings from an 18,000 TEU over a 14,000 TEU vessel reduce to 6.6%, as compared to 40% estimated by liner shipping companies solely based on the voyage costs (*4*). A significant contributor to this overestimation is underutilization, as global trade demand does not support existing capacity. One final claim (on the advantage side of the argument) is that megaships provide more flexibility for liner shipping companies to optimize capacity sharing between their alliances (*6*). On the antipodal point of the argument lie the container terminal and port operators, the public sector (responsible for maintaining the inland transport network), and a number of industry experts, indicating that megaships can cause significant congestion at terminals and the surrounding roadway network (*3*), especially if we consider increase of the demand peaks.

Despite the latter arguments, vessel size is forecasted to increase. Figure 1 presents the average size of the orderbook vessels for the largest 20 liner shipping companies as of July 2015, estimated using the Alphaliner data (*7*). Note that the average size of orderbook vessels for CSCL, APL, Zim, and Wan Hai Lines is not present, as data are not available. The majority (81%) of liner shipping companies have ordered vessels with over 10,000 TEU capacity. OOCL ordered the largest vessels: a total of 8 vessels with capacity of 144,376 TEUs (=18,047 TEUs per vessel). The vessel orderbook statistics suggests that the vessel size will increase in the nearest future. The Journal of Commerce (*8*) highlights that CMA CGM placed an order for six vessels with 14,000 TEU capacity in the first half of 2015 after an earlier order for three 20,000 TEU vessels. Maersk has recently ordered eleven 19,500 TEU vessels, while MOL and OOCL placed orders for vessels with 20,000 TEU capacity. The number of megaships is projected to increase by at least 13% by 2020 (*8*).

All these facts pose a number of questions for the scientific community (*3-6*): (1) How is the liner shipping network going to change? (2) How are MCTs (MCTs) going to accommodate megaships? (3) What type of handling equipment will be used to efficiently serve those vessels? (4) Where will the current large vessels be deployed and what will the effects be? (5) How is the inland capacity going to be expanded and how will it bear the cost? This report presents an up-to-date literature review on megaships to summarize existing research and identify areas that have not been studied.

The rest of the paper is structured as follows: The next section describes how the literature search has been performed. The third section provides an overview of collected studies, disaggregated by different topics, while the fourth section provides a summary of findings. The fifth section provides necessary conclusions and outlines potential future research directions.

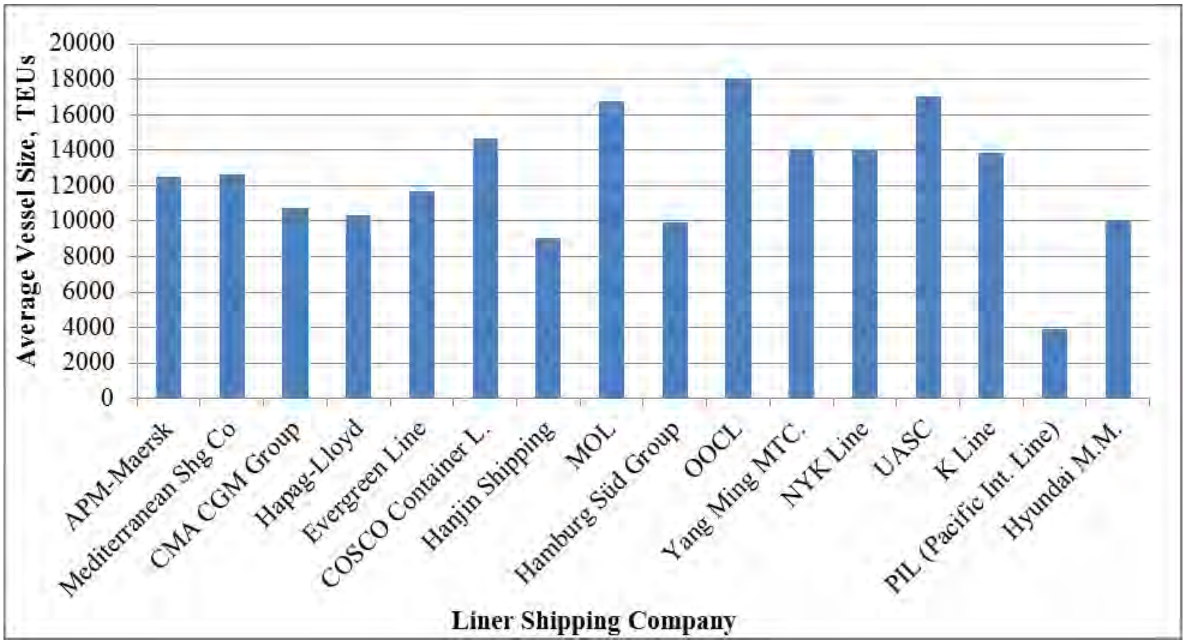

FIGURE 1 Average Size of Orderbook Vessels.

LITERATURE SEARCH

We performed an extensive literature review using various databases (Elsevier, Springer Verlag, John Wiley, Francis & Taylor, etc.), conference proceedings, and scientific manuscripts (i.e., Master Theses and Dissertations). The following keywords/phrases were used during the search: megaships, increasing size of vessels, handling equipment for megaships, terminal layout for megaships, and liner shipping network for large size vessels. A total of 52 publications were identified and grouped by various topics: 1) Economies of scale – 14% of publications, 2) Port operations – 33% of publications, 3) Liner shipping operations – 24% of publications, 4) Slow steaming – 14% of publications, and 5) Miscellaneous – 16% of publications. Distribution of publications by year is presented in Figure 2. We observe that megaships receive an increasing attention from the research community. Next we present a detailed description of the reviewed studies.

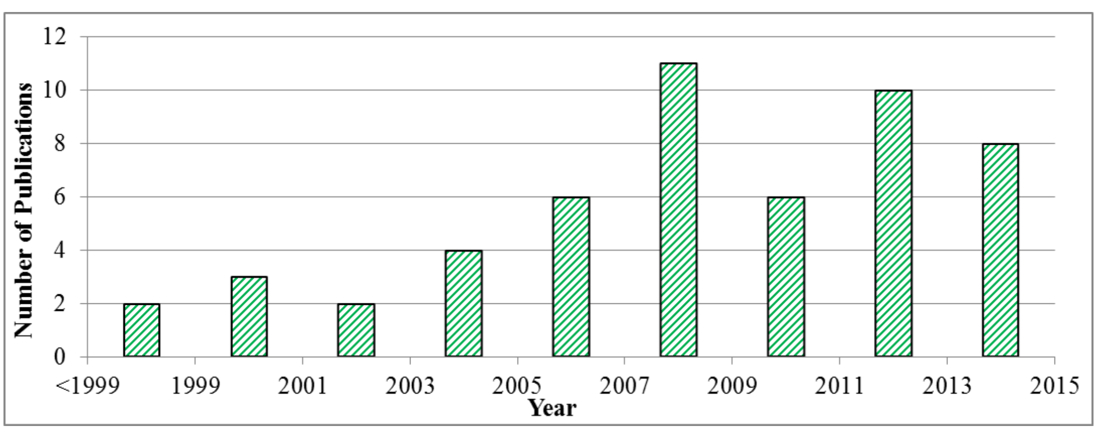

FIGURE 2 Distribution of Publications by Year.

OVERVIEW OF COLLECTED STUDIES

Economies of Scale (EOS)

EOS refer to the decrease of the unit transport cost with increasing amount of units (*9*). This subsection describes studies, discussing EOS that can be achieved from deployment of megaships.

Cullinane and Khanna (*10, 11*) developed a model to quantify potential cost savings from using megaships. The following cost components were considered: a) daily capital cost, b) daily operating cost (insurance, maintenance, crew, etc.), c) daily fuel cost per TEU, and d) daily distance. Results indicated that EOSEOS declined for routes with shorter length, the vessel cost of time in port per voyage increased with the vessel size, and the voyage cost per TEU decreased with the vessel size for Transatlantic, Transpacific, and Europe-Far East routes. Stopford (*12*) underlined that EOSEOS from megaships deployment decreased beyond 3,000 TEU and over 8,000 TEU those savings became very small. Furthermore, there are additional costs for port expansion to serve those vessels. Increasing trade volumes will mostly benefit medium size vessels. Flexibility of medium size vessels will be also in favor of logistic operators. Similar to Stopford (*12*), Van Ham (*13*) mentioned that for vessels beyond 5,000 TEU EOS diminished rapidly. The reasons for the latter are increasing capital costs, operating expenses, bunker costs, inland transport costs, and other costs. The vessel size would probably continue increasing until a certain limit, which would create too many issues for serving those vessels.

Notteboom (*14*) indicated that a 12,000 TEU vessel, sailing on the Europe-Far East trade route, could yield 11% cost savings per container as compared to a 8,000 TEU vessel and even 23% as compared to 4,000 TEU vessel. Along with EOS advantages, the following disadvantages from megaships deployment were outlined: 1) necessity of the same vessel size at each route, 2) lower flexibility as compared to medium size vessels, and 3) poor vessel space utilization. Notteboom and Rodrigue (*15*) highlighted that diseconomies of scale became a major concern at MCTMCTs. The authors mentioned than sudden changes in vessel size put a significant pressure on MCT operators.

Sys et al. (*16*) indicated that EOS were noticeable even for larger vessels (with more than8,000 TEU). However, the operating costs and the landside distribution costs should be included in the cost model to determine accurately the optimal vessel size. Along with EOS several other factors have to be considered before deployment of larger vessels, including spatial constraints at container terminals, handling equipment, intermodal capacity, and trade route characteristics.

Port Operations

As highlighted by Vis and Koster (*17*), MCT operations should be improved to efficiently serve larger vessels. This subsection discusses studies that were conducted to determine how megaships are going to affect MCT operations and how port productivity can be improved to facilitate service of megaships. The overviewed studies were grouped by different topics and are described next.

Vessel Stowage and Quay Crane Allocation/Scheduling

Several studies focused on improving vessel stowage planning, quay crane (QC) allocation and scheduling. Wilson and Roach (*18*) developed a methodology for container stowage planning.

The authors underlined importance of the efficient stowage plan especially for larger vessels. The objective of a mathematical model minimized the cargo spaces, occupied by each destination; number of re-handles; number of hatch-lids moved; number of cargo blocks, occupied by containers; and maximized the number of QCs in operation. A Tabu Search method was used to solve the problem. Computational experiments demonstrated efficiency of the proposed methodology. Lee et al. (*19*) formulated the QC scheduling problem at a MCT, taking into account non-interference constraints. The model ignored relocation time of QCs from one hold to another. The objective aimed to minimize the completion time of the last task. The authors developed a heuristic to solve the problem. Computational experiments indicated that the optimality gap for the heuristic comprised 7.08%, while the computation time did not exceed 1.0 sec for generated problem instances. A similar study was performed by Lee et al. (*20*). An Evolutionary Algorithm (EA) was developed to solve the problem. It was found that the optimality gap for the solution algorithm comprised 0.41%.

Zhang and Kim (*21*) studied dual-cycle operations of QCs at a MCT. The objective of a mixed integer programming model minimized the total turnaround time of vessels by maximizing the number of QC dual cycles. CPLEX was used to solve small size problems. The authors developed a hybrid heuristic algorithm to solve medium and large size problems. Numerical experiments were conducted based on the data collected from the Port of Busan. Results demonstrated efficiency of the proposed methodology and the solution approach. Chao and Lin (*22*) evaluated factors, influencing choice of advanced QCs at MCTs. Three advanced QC types were considered: 40 ft twin lift QCs, double-trolley QCs, and double-sided system. Two-phase approach was implemented in the study. The first phase was to construct a hierarchical evaluation structure, based on a questionnaire survey. The next step was to determine weights for the following factors: stowage, safety, productivity, and cost. An empirical study was performed based on the data, collected from the Port of Kaohsiung. Double-trolley QCs had the highest weight for stowage, while two-sided QCs had the greatest weight for safety, cost, and productivity. Chen et al. (*23*) considered quayside operations at MCT and formulated the QC scheduling problem, taking into account non-interference constraints. The objective minimized total vessel delay. A heuristic based on the Benders' cut algorithm was developed to solve the problem. It was found that the suggested solution approach outperformed the Brunch-and-Cut algorithm.

Berthing Layouts

A few studies evaluated various berthing layouts to provide efficient service of megaships. Three different berthing layouts were considered: a) conventional - containers are handled from one side of a vessel at the assigned berth (see Figure 3A); b) indented - a vessel is served at an indented berth (see Figure 3B); and c) channel - containers are handled from two sides of a vessel along the channel (see Figure 3C).

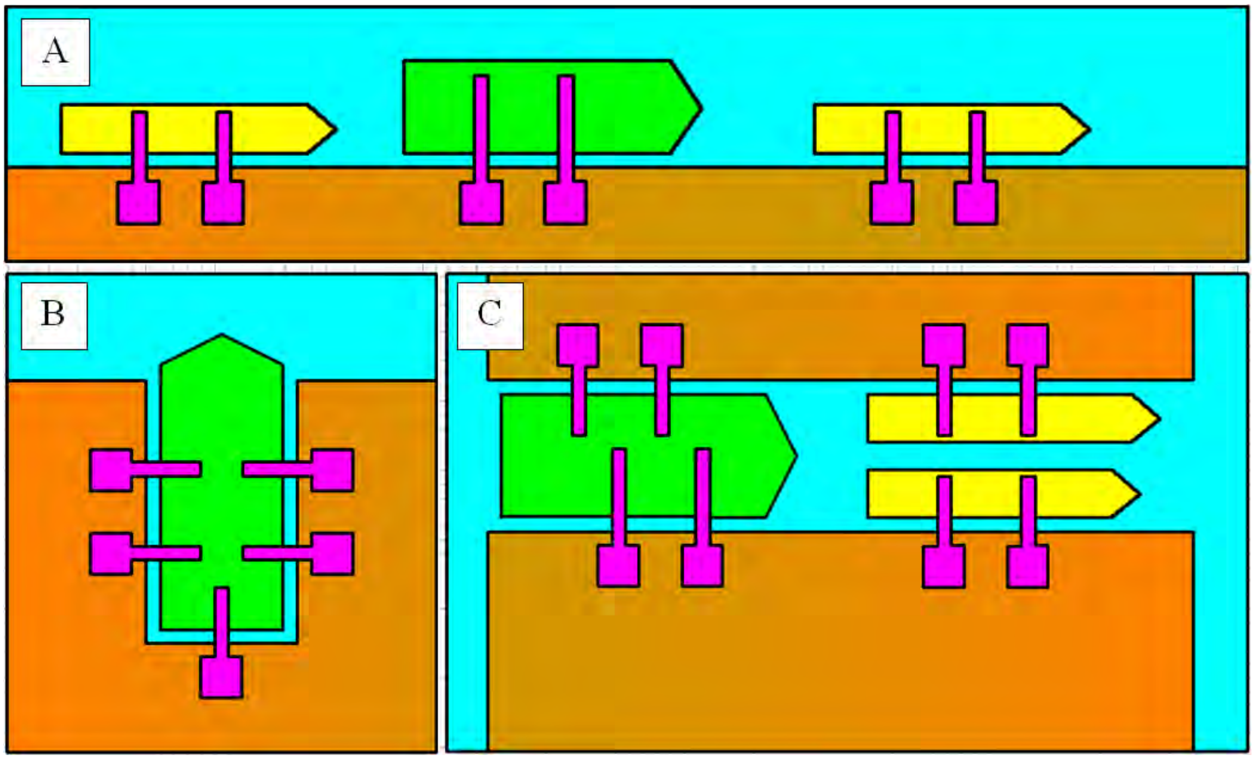

FIGURE 3 Berthing Layouts.

Imai et al. (*24*) formulated the hybrid berth allocation problem at a multi-user container terminal with indented berthing layout, where megaships were served. The objective minimized the total vessel service time. The authors considered a discrete berth spacing adding dimensional constraints. An EA was developed to solve the problem. It was found that handling of megaships was faster at the terminal with indented berthing layout, but the total service time didn't vary significantly from the terminal with conventional berthing layout. Nishimura et al. (*25*) studied storage arrangement of transshipment containers in the marshaling yard of the terminal, where megaships were served. The objective minimized the container handling and transport time from megaships to yard blocks, the container transport and handling time from yard blocks to feeder vessels, and feeder vessel waiting times. A subgradient method was used to solve the problem. Numerical experiments were performed for terminals with conventional and indented berthing layouts. It was found that the latter terminal configuration provided faster handling of megaships.

Imai et al. (*26*) investigated the hybrid berth allocation problem at a MCT, serving megaships. Three berthing layouts were considered: conventional, indented, and channel. Various vessels sizes were evaluated. The objective function aimed to minimize the total service time of vessels. The authors developed an EA to solve the problem. It was found that terminals with channel berthing layout were more efficient than terminals with conventional and indented berthing layouts, and the total service time of vessels including megaships was the shortest in the majority of cases.

Vessel Handling Systems

A few studies evaluated novel vessel handling systems, which might reduce port congestion and facilitate handling of megaships. Liftech, Inc. (*27*) and Ashar (*28*) introduced a floaterm concept to reduce port congestion and provide faster service of megaships. The main difference between floaterm and conventional MCTs is that in the former case some of import and/or transshipment containers are handled by off-shore QCs and placed on container barges, which are further towed by push boats to assigned feeder vessels or floating yard. The floaterm concept includes two-sided operations (when a vessel is served from one side using on-shore QCs and from the other side using floating QCs) and midstream operations (when a vessel is served off-shore using floating QCs only). Dulebenets et al. (*29*) compared conventional and floaterm terminal terminals (two-sided operations). Two simulation models were developed to evaluate performance of both terminals under normal and disruptive operating conditions. Numerical experiments indicated that the floaterm concept could significantly reduce the number of handling equipment from landside, provide higher QC productivity, and improve resilience of terminal operations.

Shin and Lee (*30*) formulated the QC scheduling problem for a mobile floating port system (the mobile harbor), used for handling vessels off-shore. The mobile harbor system is represented by a container barge with installed QC. The objective minimized the last task completion time. Containers were placed on the mobile harbor, taking into account the stability conditions. The authors developed an EA and a Local Search heuristic to solve the problem. Numerical experiments indicated that both solution approaches were able to obtain good quality solutions. It was found that the Local Search heuristic was sensitive to the stability constraint. Nam and Lee (*31*) formulated the QC scheduling problem for a mobile harbor system, which allowed handling containers from vessels, anchored in the sea. The objective minimized the last task completion time. The authors took into account safety distances between floating mobile harbors. A Rule-Based Algorithm (RBA) and a Random Key based Genetic Algorithm (RQGA) were presented to solve the problem. Numerical examples indicated that RQGA outperformed RBA in terms of solution quality and computational time.

Miscellaneous

Several studies described how ports would be affected with increasing size of vessels. Hacegaba (*32*) indicated that United States (U.S.) ports expected to spend $46 billion on port improvements by 2017 to better accommodate megaships. It was mentioned that megaships significantly affected the port infrastructure, including access channel width and depth, air draft, depth alongside, quay length, handling equipment, landside capacity, hinterland connections, etc. The following strategies were recommended to Port Authorities to prepare for the increasing demand and megaships: 1) collaboration, 2) improve terminal productivity, and 3) upgrade infrastructure. Notteboom and Rodrigue (*33*) underline that spatial constraints significantly affect the port development and feasibility of serving larger vessels.

Liner Shipping Operations

Liner Shipping Network Configuration

Several studies were conducted to determine the optimal size of vessels for different liner shipping network configurations. Typically two alternatives were considered: hub-and-spoke (H&S) network and multi-port calling (MPC) network. In H&S network there are two groups of ports: hub ports and feeder ports (see Figure 4A). The cargo between two regions (R1 and R2) is transported via the main line (typically by larger vessels), connecting hub ports. From hub ports the cargo is transported to feeder ports (typically by smaller vessels). In MPC network there is no distinction between hub and feeder ports (see Figure 4B). A vessel can sail from a port to any other port, belonging to the given trade route.

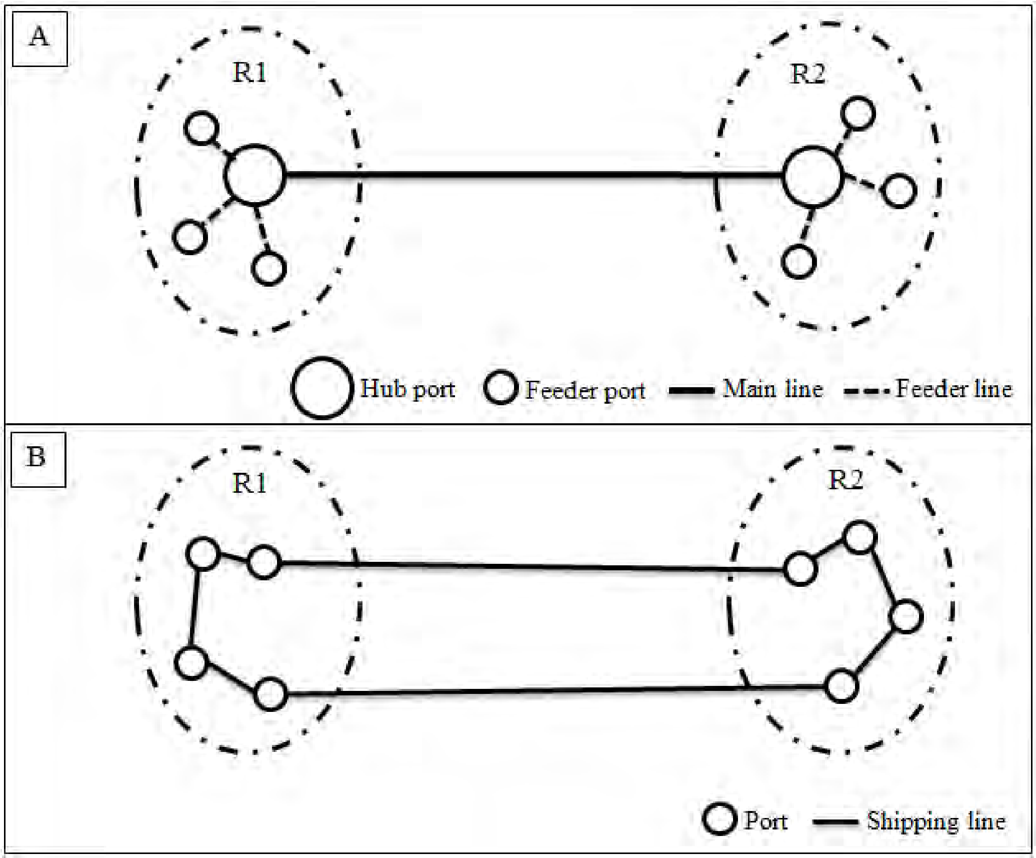

FIGURE 4 Hub-and-Spoke and Multi-Port Calling Networks.

Baird (*34*) mentioned that major ocean carriers and alliances, deploying large containerships, used H&S network. It was underlined that a detailed cost analysis should be conducted to determine if the MPC or H&S network would be more efficient for the given service route. Furthermore, multiple factors should be taken into account before deployment of larger vessels, including channel depth, port draft, handling equipment, storage space, etc. Imai et al. (*35*) performed a study to evaluate viability of megaships. Two liner service networks were considered: MPC with conventional size vessels and H&S with megaships. The objective minimized the total transit time weighted by shipment volume. A heuristic was developed to solve the problem. Numerical experiments were performed for the Asia-Europe and the Asia-North America trade routes. It was found that megaships were competitive in all scenarios for the Asia-Europe trade route, but for the Asia-North America trade route megaships were viable only in cases with low freight rates and feeder costs. A similar study was performed by Chen and Zhang (*36*).

Fremont (*37*) indicated that both MPC and H&S networks were compatible and could complement each other. H&S network allows liner shipping companies serve wider markets, enable them to deploy larger vessels, and offer different services to customers. MPC network can be used for handling large shipping volumes between markets. The paper underlined importance of hub ports for H&S network. Imai et al. (*38*) examined MPC & H&S networks for different vessel sizes. The objective minimized the total transportation cost, including capital fleet cost, empty container repositioning cost, empty container storage cost, and container leasing costs. MPC network was served by 5,000 TEU vessels, while H&S network was served by 10,000 TEU vessels. The problem was solved using LINGO. Numerical experiments were performed for the Asia-Europe and the Asia-North America routes. It was found that MPC network was superior in terms of the total cost, while H&S network was more advantageous for the Asia-Europe route and large liner shipping companies.

Vessel Routing and Scheduling

Another group of studies focused on development of mathematical models and solution algorithms to design the liner shipping route and determine the optimal size of vessel to be deployed, sailing speed, and service frequency. Hsu and Hsieh (*39*) formulated a bi-objective model to determine the optimal shipping route, vessel size, and service frequency for H&S network. The first objective minimized the total shipping costs, while the second one minimized the total inventory costs. A case study was conducted for the Trans-Pacific trade route. Results demonstrated efficiency of the suggested methodology. Karlaftis et al. (*40*) studied vessel routing problem with time deadlines, simultaneous deliveries and pick-ups. The objective minimized the total transportation cost. A hybrid EA was developed to solve the problem. Numerical experiments were performed for the vessel fleet, serving ports in Aegean Sea. Results indicated that use of larger vessels could lead to smaller fleet, but increased port arrival time delays.

Meng and Wang (*41*) developed a model to determine service frequency, fleet deployment plan, and sailing speed for a long-haul liner service route. The objective of a mixed integer non-linear program minimized the total daily operating cost. A linear approximation method was used to linearize a non-linear bunker cost component. Then a linear program was solved using the Branch-and-Bound algorithm. Numerical experiments were conducted based on the operational data provided by SCX liner shipping company. It was found that express services might require deployment of more vessels with lower capacity and higher frequency. Wang and Meng (*42*) studied a linear vessel fleet deployment problem with container transshipment operations. The objective minimized the total operating cost. CPLEX was used to solve the problem. Computations experiments were conducted for the Asia–Europe–Oceania network with 46 ports of call. The developed model provided the optimal vessel size for each one of the considered routes and vessel utilization.

Wang et al. (*43*) developed three game-theoretical models to analyze competition between two liner shipping companies: Nash competition, Stackelberg competition, and deterrence game. Computational examples were presented for Pacific International Line service. Results indicated that increasing size of vessels might be more economic decision than updating the service frequency in case of increasing demand. Huang et al. (*44*) studied the liner shipping network design and fleet deployment problem with empty container repositioning. The objective minimized the total operating cost, including bunker costs, vessel operating cost, and empty/laden container handling costs. CPLEX was used to solve the problem. Numerical experiments were performed for the Asia–Europe–Oceania network. It was found that larger vessels should be deployed on routes with two or more hub ports. Wang (*45*) studied the problem of the optimal sequence of vessels in a string, taking into account that size of vessels in a string might vary and their order could affect container delays due to demand uncertainty. A set of rules was proposed to for selecting a vessel string. Numerical experiments demonstrated that the suggested methodology could yield substantial cost savings.

Slow Steaming

Slow steaming (i.e., a vessel sails at lower than its design speed), became a common strategy among liner shipping companies to reduce bunker consumption in the beginning of the 21s century (*46*). This subsection discuses advantages and disadvantages of slow steaming and how slow steaming affects performance of megaships.

Notteboom and Vernimmen (*47*) assessed the effects of high fuel cost on the liner service configuration for the Europe–Far East trade. The paper underlines that slow steaming allows liner shipping companies to reduce bunker consumption, but increases the transit time. Furthermore, slow steaming would require deployment of more megaships to provide the agreed service frequency at each port of call. Cariou (*48*) investigated the impact of slow steaming on the carbon dioxide emissions. The author indicated that 75.5% of larger vessels (with +8,000 TEUs capacity) use slow steaming strategy to reduce bunker consumption (hence carbon dioxide emissions) and save associated costs. Psaraftis and Kontovas (*49*) underlined that along with slow steaming certain liner shipping companies also used another strategy to decrease bunker consumption, which consisted in design of vessels with reduced horsepower engines. The authors mentioned that 18,000 TEU Triple E vessels have the maximum speed of 19 knots, which is 6.5 knots lower as compared to Emma Maersk.

Song and Dong (*50*) considered the long-haul service route design problem. The objective minimized the total operating cost, including vessel operating cost, fuel consumption cost, port access and handling cost, and cargo inventory costs. A three-stage optimization procedure was developed to solve the problem. Computational examples were presented for the Asia-Europe trade route. Results showed that more vessels with lower speeds were deployed for the cases when inventory costs were not considered. Guan et al. (*51*) investigated operations of the megaships main engine under slow steaming condition. A two-stroke main engine was simulated in MATLAB/Simulink environment. The engine simulation tool was found to be efficient in predicting the engine steady state performance under slow steaming. Psaraftis and Kontovas (*52*) and Kontovas (*53*) indicate that the bunker consumption for a typical small/medium size vessel is proportional to the sailing speed in the power of 3, while the bunker consumption for a large high-speed vessel is proportional to the sailing speed in the power of 4.5. Hence, slow steaming is crucial for megaships to reduce bunker consumption.

Miscellaneous

This subsection describes all other studies that were found as a result of performed literature search and did not fall under any of the groups, presented earlier.

Robinson (*54*) conducted a study to determine the relationship between the vessel size and turnaround time at the Port of Hong Kong. The data were collected for 1,216 general cargo vessels. Analysis results indicated that the vessel turnaround time was not a simple function and not solely dependent on the vessel size. However, for the majority of cases it was found that larger vessels were served faster at the Port of Hong Kong. Scinas and Papadimitriou (*55*) examined the impact of megaships deployment at routes, passing through the Mediterranean ports. It was underlined that ports had to increase their capacity to become hubs and be able to serve large size vessels. Furthermore, liner shipping companies would become the dominant players, having right to choose the port of call. The paper mentioned that the Mediterranean ports would be able to handle megaships, but hinterland connections should be improved. Rordigue and Notteboom (*56*) analyzed challenges in the maritime-land interface. The study highlights that larger vessels visit less ports of call and concentrate their services in large markets. Increasing container volumes, delivered by larger vessels, also increase traffic volumes on gateways, which require upgrading not only container terminal, but also hinterland capacity.

Cariou (*57*) overviewed tendencies in liner shipping and underlined that the largest ocean carriers (i.e., Maersk, MSC, and CMA CGM) increased order of the large size vessels. Based on analysis of the future demand, it was found that continuous ordering of large vessels might cause substantial overcapacity. Giulia et al. (*58*) performed the analysis of liner shipping tendencies and highlighted increasing over the years size of vessels. The authors mentioned that several factors should be considered before deployment of megaships, including demand, naval vessel structure, berth draft, handling equipment, and environmental issues. Examples for Port of Rotterdam and Port of Antwerp were presented to showcase monetary benefits that could be achieved by Port Authorities from serving megaships.

Gadhia et al. (*59*) grouped liner shipping companies into four clusters based on their average vessel size: 1) networking companies, 2) concentrators, 3) niche players, and 4) going what direction. Companies of the first cluster have a global network and allocate significant capacity (Maersk, MSC, CMA CGM), while the second cluster companies dedicate their resource to only specific routes (OOCL, K line, OOIL). The third cluster companies have a global network, but not willing to allocate much capacity (PIL), while the fourth cluster includes all the others (MOL, NYK, CSAV, COSCO, etc.). Streng (*60*) studied possible effects of megaships on the carrier market, Port Authorities, and container terminal operators. Carrier market effects were divided into three groups: 1) horizontal integration - smaller companies integrate, 2) vertical integration – two links of the supply chain become one, and 3) other effects. It was mentioned that Ports Authorities had to make their ports to be attractive for the liner shipping companies, while MCT operators had to upgrade their terminals to serve larger vessels, including purchase of new equipment, increasing storage space, improve productivity, etc.

Almaz and Altiok (*61*) built a simulation model to emulate vessel traffic in Delaware River and assess the effect of its deepening on the port performance. As a result of a scenario analysis it was found that shift to larger vessels would increase port times, but decrease the total number of calls per year. Furthermore, increasing size of vessels would lead to increased anchorage delays at the port. Fan et al. (*62*) conducted a comprehensive analysis of the U.S. intermodal network, and concluded that congestion existed at most of U.S. ports. The authors outlined alternatives for reducing the port congestion, including increasing port charges, demand diversion to other ports, increasing port capacity, and dredging that would allow service of larger vessels.

DISCUSSION/SUMMARY

This section outlines findings that were revealed as a result of the conducted literature review for each one of the considered topics. A brief summary is provided in Table 1 for each study, including authors, study objectives, and notes on the solution approach used (if applicable) and the main conclusions.

EOS

One of megaships advantages is EOS, which means that the total voyage cost (including weekly operating cost, bunker consumption cost, emissions, etc.) per TEU decrease with increasing size of vessel. All collected studies (under category "EOS") acknowledge economies of scales for megaships, however, EOS decline with the voyage length (*10, 11*). Furthermore, for very large vessels (e.g., +8,000 TEUs) EOS become very small (*12, 13*). All collected studies also underline that there are diseconomies of scale for megaships at MCTs (*10-16*). MCT operators have to upgrade their terminals to be able to serve megaships, including increase in water depth and air draft, new handling equipment, expand the storage capacity, etc. (*12-16*).

Continuous increase in vessel size puts more pressure on MCT operators (*14, 15*). Some experts indicate that medium vessels have more flexibility as compared to megaships (*12, 14*). Sys et al. (*16*) highlighted that multiple factors have to be considered in the cost model when deciding on the vessel size, not just the total voyage cost. Van Ham (*13*) expects that the size of vessels will continue increasing until a certain limit is reached.

Port Operations

The first group of collected studies aimed to improve vessel stowage planning, QC allocation and scheduling. Wilson and Roach (*18*) proposed a new methodology for stowage planning and underlined that efficient stowage plan would facilitate service of megaships. Lee et al. (*18, 19*) and Chen et al. (*23*) developed algorithms for QC scheduling problem with non-interference constraints. Zhang and Kim (*21*) proposed a hybrid algorithm for minimizing the total vessel turnaround time, while Chao et al. (*22*) determined factors, affecting choice of different QC configurations.

The second group of studies evaluated alternative berthing layouts that may decrease turnaround time of megaships. Imai et al. (*24*) and Nishimura et al. (*25*) indicated that handling of megaships at the terminal with indented berthing layout was faster as compared to the terminal with conventional berthing layout. However, the total vessel service time is approximately the same for both conventional and indented berthing layouts. Imai et al. (*26*) introduced a new channel berthing layout, when a megaship was moored along the channel. Numerical experiments indicated that the channel berthing layout was superior to the indented and conventional berthing layouts in terms of total vessel service time for the majority of cases.

Another group of studies focused on new container handling systems that might reduce congestion and provide efficient service of megaships. Liftech (*27*) and Ashar (*28*) proposed a floaterm concept, which includes two-sided and midstream operations. In case of two-sided operations, floating QCs are introduced to handle import and/or transshipment containers along with on-shore QCs. In case of midstream operations, the vessel is served completely off-shore. Dulebenets et al. (*29*) conducted a comprehensive simulation analysis of the floaterm MCT with two-sided operations, and indicated that the floaterm concept could significantly reduce the number of handling equipment from landside, provide higher QC productivity, and improve resilience of terminal operations. Shin and Lee (*30*) and Nam and Lee (*31*) modeled a mobile harbor system, which is represented by a container barge with installed QC.

Liner Shipping Operations

Several studies were performed to determine the optimal size of vessels for different liner shipping network configurations (*34-39*). Liner shipping companies with preference to deploy megaships, typically use H&S network (*34*). Most of studies indicate that the network and vessel size selection depends on the trade route type (*35, 36, 38*). For example, megaships are efficient for the Asia-Europe trade route with H&S network, but for the Asia-North America trade route with H&S network they will be efficient only in cases with low freight rates and feeder costs. A comprehensive cost analysis should be conducted before deciding on the network type (*34*).

Another group of studies propose mathematical models and solution algorithms to design the liner shipping route and determine the optimal size of vessel to be deployed, sailing speed, and service frequency (*40-44*). Karlaftis et al. (*40*) highlighted that use of larger vessels could lead to smaller fleet, but increased port arrival time delays. Meng and Wang (*41*) indicate that express services might require deployment of more vessels with lower capacity and higher frequency. Increasing size of vessels might be more economic decision than updating the service frequency in case of increasing demand (*43*). Huang et al. (*44*) found that larger vessels should be deployed on routes with two or more hub ports.

Slow Steaming

Slow steaming, when a vessel sails slower than its design speed, is an important strategy for reducing bunker consumption of megaships. The latter can be explained by the fact that bunker consumption for large vessels increases much faster with sailing speed as compared to small and medium size vessels (*52, 53*). Along with slow steaming certain liner shipping companies also use another strategy to reduce bunker consumption, which consists in design of vessels with reduced horsepower engines (*49*). However, slow steaming would require deployment of more megaships to provide the agreed service frequency at each port of call (*47*). Furthermore, inventory costs should be taken into consideration, when assessing monetary benefits from slow steaming (*50*).

Miscellaneous

Robinson (*54*) performed an empirical study to evaluate the vessel turnaround time at the Port of Hong Kong and found that for the majority of cases larger vessels were served faster. Scinas and Papadimitriou (*55*) underlined that the Mediterranean ports would be able to handle megaships, but hinterland connections should be improved. Rordigue and Notteboom (*56*) mention that deployment of larger vessels would require upgrading not only container terminal, but also hinterland capacity. Continuous ordering of megaships would result in a substantial overcapacity (*57*). Deployment of megaships would affect multiple supply chain players, including liner shipping companies, Port Authorities, and MCT operators (*58, 60*). Shift to larger vessels would increase port times, but decrease the total number of calls per year (*61*).

TABLE 1 Literature Summary

a/a	*Authors*	*Year*	*Objective*	*Notes*
			EOS	
1	Cullinane & Khanna	1999	Quantify cost savings from using megaships	EOSs declined for routes with shorter length
2	Cullinane & Khanna	2000		
3	Stopford	2002	Cost analysis for megaships	EOS are negligible for very large vessels
4	Notteboom	2004	Overview of container shipping and ports	Along with EOS megaships have disadvantages
5	Van Ham	2005	Feasibility of megaships	The vessel size will continue increasing until a certain limit
6	Sys et al.	2008	Determine the optimal vessel size	The cost model should include all necessary components
7	Notteboom & Rodrigue	2009	Future tendencies in containerization	Diseconomies of scale at MCTs
			Port Operations	
8	Wilson & Roach	2000	Optimize stowage planning	Tabu Search to solve the problem
9	Vis & Koster	2003	Overview of MCT operation	Necessity of improving terminal operations to serve larger vessels
10	Notteboom & Rodrigue	2005	New tendencies in port development	Spatial constraints affect feasibility of serving larger vessels
11	Imai et al.	2007	Minimize the total vessel service time	Shorter handling time of megaships at the terminal with indented berthing layout
12	Liftech, Inc.	2007	Suggested a floaterm concept	The concept will facilitate service of megaships
13	Lee et al.	2008 a	Minimize the makespan	EA to solve the problem
14	Lee et al.	2008 b	Minimize the makespan	Heuristic to solve the problem
15	Nishimura et al.	2009	Improve storage operations in the marshaling yard	Indented berthing layout provided faster handling time of megaships
16	Zhang & Kim	2009	Minimize the total vessel turnaround time	A hybrid heuristic algorithm to solve the problem
17	Chao & Lin	2011	Compare various QC configurations	Determined factors affecting choice of the QC configuration
18	Ashar	2012	Advantages of the floaterm concept	The concept will facilitate service of megaships
19	Chen et al.	2012	Minimize the total vessel delays	The developed heuristic outperformed the Brunch-and-Cut algorithm
20	Nam & Lee	2012	Minimize the makespan	Random Key based Genetic Algorithm outperformed the Rule-Based Algorithm
21	Shin & Lee	2012	Minimize the makespan	EA and Local Search heuristic to solve the problem
22	Imai et al.	2013	Minimize the total vessel service time	Channel layout is more efficient that conventional and indented layouts
23	Hacegaba	2014	Determine effects of megaships on U.S. ports	Suggested several strategies to serve the increasing demand and megaships
24	Dulebenets et al.	2015	Compared conventional and floaterm MCTs	The floaterm concept could improve terminal operations and terminal resilience

TABLE 1 Literature Summary (Continued)

a/a	*Authors*	*Year*	*Objective*	*Notes*
Liner Shipping operations				
25	Baird	2006	Optimize hub location in Europe	Multiple factors should be considered before megaships deployment
26	Imai et al.	2006	Evaluate viability of megaships	Megaships were competitive for the Asia-Europe route, but viable for the Asia-North America route only in cases with low freight rates and feeder costs
27	Fremont	2007	Evaluate global maritime networks	MPC and H&S can complement each other
28	Hsu & Hsieh	2007	Minimize the total shipping and inventory costs	A bi-objective model was solved using Mathematica
29	Chen & Zhang	2008	Evaluate viability of megaships	Megaships are efficient for the Asia-Europe route
30	Imai et al.	2009	Minimize the total transportation cost	MPC network was superior in terms of the total cost; H&S was more advantageous for the Asia-Europe route
31	Karlaftis et al.	2009	Minimize the total transportation cost	Use of larger vessels could lead to smaller fleet, but increased port arrival time delays
32	Meng & Wang	2011	Minimized the total daily operating cost	Express services might require deployment of more vessels with lower capacity and higher frequency
33	Wang & Meng	2012	Minimize the total operating cost	Provided the optimal vessel size for each one of the considered routes and vessel utilization
34	Wang et al.	2014	Analyze competition between two liner shipping companies	Increasing size of vessels might be more economic decision than updating the service frequency in case of increasing demand
35	Huang et al.	2015	Minimize the total operating cost	Larger vessels should be deployed on routes with two or more hub ports
36	Wang	2015	Determine the optimal sequence of vessels in a string	A set of rules was proposed to for selecting a vessel string
Slow Steaming				
37	Notteboom & Vernimmen	2009	Assess the effects of high fuel cost on the liner service configuration	Slow steaming would require deployment of more megaships to provide the agreed service frequency
38	Golias et al.	2010	Minimize the total vessel service time, delayed departures, fuel consumption, and emissions productions	EA to solve the problem
39	Cariou	2011	Investigate the impact of slow steaming on the carbon dioxide emissions	75.5% of larger vessels use slow steaming strategy to reduce bunker consumption
40	Psaraftis & Kontovas	2013	Overview of speed models in marine transportation	Design of vessels with reduced horsepower engines to decrease bunker consumption
41	Song & Dong	2013	Minimize the total operating cost	More vessels with lower speeds were deployed for the cases when inventory costs were not considered
42	Guan et al.	2014	Investigate operations of the megaships' main engine under slow steaming	Model in MATLAB/Simulink environment
43	Kontovas	2014	Minimize the total transportation cost	Bunker consumption increase faster with sailing speed for larger vessels
44	Psaraftis & Kontovas	2014	Overview of speed optimization models	

TABLE 1 Literature Summary (Continued)

a/a	*Authors*	*Year*	*Objective*	*Notes*
Miscellaneous				
45	Robinson	1978	Evaluated vessel turnaround time at the Port of Hong Kong	Larger vessels were typically served faster
46	Scinas & Papadimitriou	2001	Examine the impact of megaships deployment	Mediterranean ports would be able to handle megaships, but hinterland connections should be improved
47	Rodrigue & Notteboom	2005	Analyze challenges in the maritime-land interface	Larger vessels require upgrading not only container terminal, but also hinterland capacity
48	Cariou	2008	Overview of liner shipping strategies	Continuous ordering of large vessels might cause substantial overcapacity
49	Gadhia et al.	2011	Evaluating of liner shipping networks	Provided classification of liner shipping companies by the average vessel size
50	Streng	2011	Determine consequences of megaships	Outlined effects of megaships of the global trade, Port Authorities, and marine terminal operators.
51	Almaz & Altiok	2012	Emulate vessel traffic in Delaware River	Larger vessels would increase port times, but decrease the total number of calls per year
52	Fan et al.	2012	Comprehensive analysis of the U.S. intermodal network	Outlined alternatives for improving port operations to serve the increasing demand and megaships

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Over the last decades the size of vessels, deployed by liner shipping companies on trade routes, significantly increased. Megaships provide lower voyage cost per TEU as compared to medium and small size vessels. Furthermore, megaships provide more flexibility for liner shipping companies as they allow easier sharing of demand between alliance partners. However, other supply chain players have to upgrade their infrastructure to serve the increasing demand and large size vessels. This report presented an up-to-date and comprehensive overview of the scientific literature related to megaships. The reviewed studies discussed the effects of megaships on liner shipping, MCT and hinterland operators, and provided mathematical models and solution algorithms for MCTs that serve megaships and liner shipping networks, where megaships are deployed. Based on the literature review, future research may focus on the following areas to address possible problems for all the supply chain stakeholders and to achieve maximum benefits and minimum externalities/costs from the introduction of megaships.

- Development of a cost model, which accounts for all transportation related costs, including weekly vessel operating costs, bunker consumption costs, port handling costs, penalties due to late port arrivals, inland transportation costs, etc. The cost model will allow liner shipping companies to have more accurate cost estimates of using megaships instead of basing the analysis solely on EOS (which are applicable only for voyage costs).
- There is only one study on the channel berthing layout, conducted by Imai et al. (*26*). Since the channel berthing layout is more efficient for service of megaships as compared to indented and conventional berthing layouts, future research should focus on modeling MCT operations with the channel berthing layout.

- Port expansion for serving megaships may be very expensive. Dredging is costly and also causes environmental issues. Furthermore, MCT operators have to purchase new handling equipment, expand their marshaling yard, upgrade inland capacity, etc. A few studies (*27-31*) propose handling of megaships off-shore, which might be more efficient alternative for MCT operators. Future research can continue development of alternative container handling systems for megaships.
- A few studies were conducted to determine the optimal size of vessels for H&S and MPC liner shipping network configurations (*34-39*). Future research can focus on development of a guidebook, which will provide a set of guidelines for liner shipping companies and assist in liner shipping route design for megaships.
- Slow steaming allows liner shipping companies significantly reduce the bunker consumption cost for megaships. However, there are additional factors that have to be considered, when selecting the sailing speed, including a) reduction in sailing speed increases the number of deployed vessels to meet the agreed frequency of service, b) reduction is sailing speed increases the transit time, c) reduction is sailing speed increases inventory costs, etc. Future research can focus on development of the model, which will account for all those factors and assist liner shipping companies in making accurate decisions on sailing speed of megaships.
- Taking into account current shipping volumes, megaships have a lot of excess capacity (*12, 13, 57*). The scope of future research could focus on developing a set of alternatives that will allow liner shipping companies to improve their capacity utilization (e.g., via additional agreements with other liner shipping companies).
- New collaborative agreements between liner shipping companies, MCT operators, and inland transport providers to share capacity and efficiently serve megaships.
- Individual ports in the U.S. and Europe will have difficulty imposing significant costs on cargo to fund port and inland connection expansion. Research is needed to develop policies and funding mechanisms to internalize these costs and identify the stakeholder share.

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