ΕΛ.Ι.Ν.Τ.

ΕΛΛΗΝΙΚΟ ΙΝΣΤΙΤΟΥΤΟ ΝΑΥΤΙΚΗΣ ΤΕΧΝΟΛΟΓΙΑΣ
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ΒΙΒΛΟΣ ΝΑΥΤΙΚΗΣ ΤΕΧΝΟΛΟΓΙΑΣ

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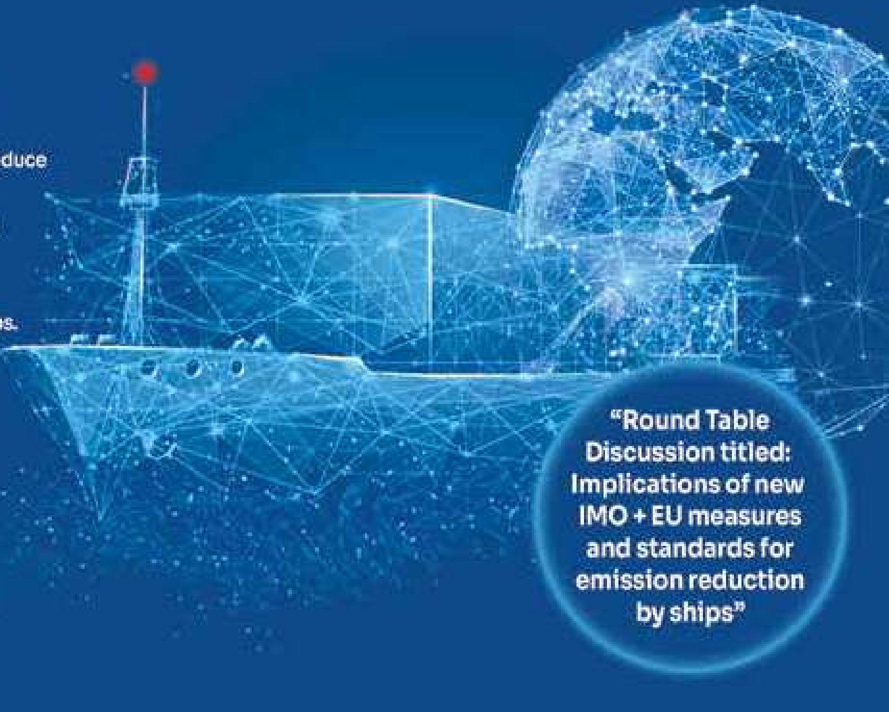

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04 REDESIGNING MEGA CONTAINERSHIPS TO ACCOMMODATE CARGO HANDLING FROM BOTH SIDES: A TECHNO-ECONOMIC STUDY

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04 REDESIGNING MEGA CONTAINERSHIPS TO ACCOMMODATE CARGO HANDLING FROM BOTH SIDES: A TECHNO-ECONOMIC STUDY

ABSTRACT

In recent years container vessels have been growing in size aiming to enjoy economies of scale. However, further increases in size are becoming more difficult due to navigational restrictions, and current quayside cargo handling equipment. As the vessels are getting bigger, the overall cargo handling times at port are increased. Making ship to shore operations more efficient is a contemporary maritime goal. In this work, changes to the proportions of the main dimensions of large containerships were investigated, aiming at making such vessels work more efficiently in association with the cargo handling concept, COFASTRANS. The analysis was made for two case studies: six new vessel designs were proposed in each case, maintaining in either case the overall ship TEU capacity. A preliminary design for all these cases was made and a software tool was developed for calculating cargo handling times. Finally, an economic evaluation was conducted, from a shipowner's perspective.

Key words: COFASTRANS; ship-to-shore; ultra large container vessels; mega ships; ship preliminary design; cargo handling; indented berth; container terminal.

1. INTRODUCTION

High efficiency has become an integral part of modern shipping. Shipping industry stakeholders, ship owners and managers aim at profit maximization and saving time is a key factor to this end. Transportation of containers by sea is divided in two legs: time at sea and time in port. The former is the time needed for the vessel to cover a specific route, while the latter is the time that the vessel remains at port, including the operation of cargo handling, as well as potential delays.

Justifiably, attempts have focused on reducing port time. This need, in conjunction with the problems and high costs of the current quayside crane technology, indicate that some changes must be made. Some new concepts have been proposed as solutions. In our opinion, the most appealing one is the Container Vessel Fast Transshipment (COFASTRANS) system, which includes an indented berth and Ship-to-Shore Portal Cranes (SSPCs) for cargo handling from both sides of the berth (see section 2.2).

The aim of this work is to investigate possible required alterations in the usual proportions of the main dimensions of Ultra Large Container Vessels (ULCVs), so as to comply better with the COFASTRANS system. Hence, vessel modifications were made in two case studies. In each case study, six different designs were investigated, keeping the total ship TEU capacity constant. A software tool has been developed for calculating loading/unloading times of each case. Lastly, a techno-economic assessment was conducted (Tsaganos 2020).

2. QUAYSIDE CONTAINER HANDLING SYSTEMS

2.1 DRAWBACKS OF CURRENT TECHNOLOGY

The current quayside container handling technology is consisted of Ship-to-Shore-Gantry (SSGs) cranes. SSGs are multi-storey structures moving on rails. Typically, in most ports, five or six cranes are deployed along a mega vessel. The trolley is the moving part of the crane, which runs the trajectory from ship to shore and vice versa, whereas the spreader is attached to the trolley and is the connection between the container and the trolley. Common types of spreaders are the single lift (1 TEU), twin lift (2 TEU or 1 FEU) and tandem lift (4 TEU or 2 FEU).

There are three major problems that terminal operators face when dealing with mega container vessels with increased vessel beam:

- As the crane boom length is increased, the more counter weight has to be placed on the other side to prevent the crane from toppling over. Since heavier cantilevers are required, the construction and maintenance costs will be increased.
- The further out the trolley has to reach, the longer it will take it to get there. To avoid this, more powerful trolley and crane machinery will be required. However, trolley speeds are currently at their maximum. The modifications in the entire crane structure needed, would make the design more complex and heavier.
- Larger vessels with higher TEU capacities will increase the transshipment rates in container terminals. Ports should have the ability to handle higher rates by making the whole transshipment process faster by using more container terminal vehicles etc.

According to the above, the beam of the vessels cannot increase beyond the current width (60-62 m), making increase in length the only possible way to increase ship size. This is fraught with problems, the most obvious being reduced maneuverability (important in inside ports), navigational restrictions (e.g. shallow waters in ports, inland waterways, canals, sea paths, bridges etc.), and demand for structures with higher longitudinal strength that are stiffer and heavier. Many attempts have been made to find a solution such as Ceres Paragon (Young 2012), 'FastNet' (Port Technology 2011) and GRID project (GRID Logistics Inc. n.d). More details of these concepts can be found in (Tsaganos 2020). However, the most appealing proposal seems to be the COFASTRANS system, which includes an indented berth and Ship-to-Shore Portal Cranes (SSPCs) for cargo handling from both sides of the berth.

2.2 THE COFASTRANS SYSTEM

The objective of this concept is to improve the efficiency of container transportation in terms of time, carrier costs, and environmental impacts. The new concept SSPCs have been designed so that each crane can line up and address simultaneously two non-adjacent bays of the container vessel (two spanning beams, which are set about 30m apart), each bay being serviced by two trolleys, so as to provide four independent lifting points per crane (Figure 1). The buffer-to-buffer length of the cranes is less than 53m, allowing a maximum of five SSPC units to be deployed over a 400m long vessel (Rankine G. 2015). It is considered that acceptable efficiency can be achieved by deploying only three or four SSPCs, the use of the fourth still being under investigation for economic reasons (Oja H. 2019). Only three SSPC units were considered in this study, resulting in the simultaneous operation of twelve spreaders over six bays of the vessel, corresponding to the situation where six conventional cranes with six trolleys are deployed over six bays of the vessel.

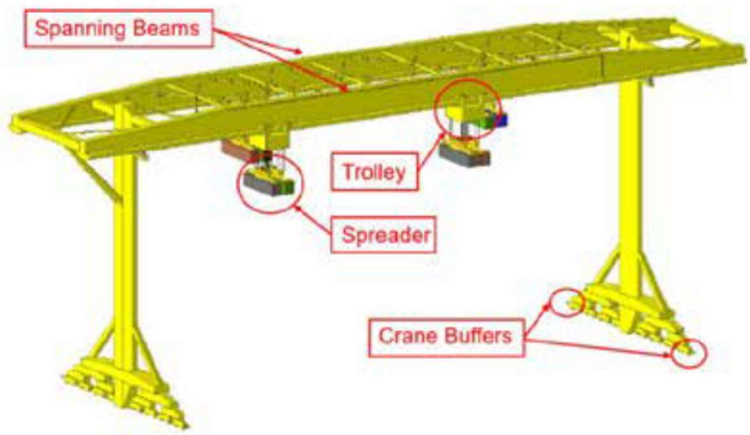

Figure 1: Ship-to-Shore Portal crane.
Source: (Rankine et al. 2018)

Table 1 presents the typical geometric and technical characteristics of both the SSG and the SSPC concept considered in the present study (Rankine G. 2015 & Nevsimal and Oja 2018). Respectively, Figure 2 depicts their geometric characteristics.

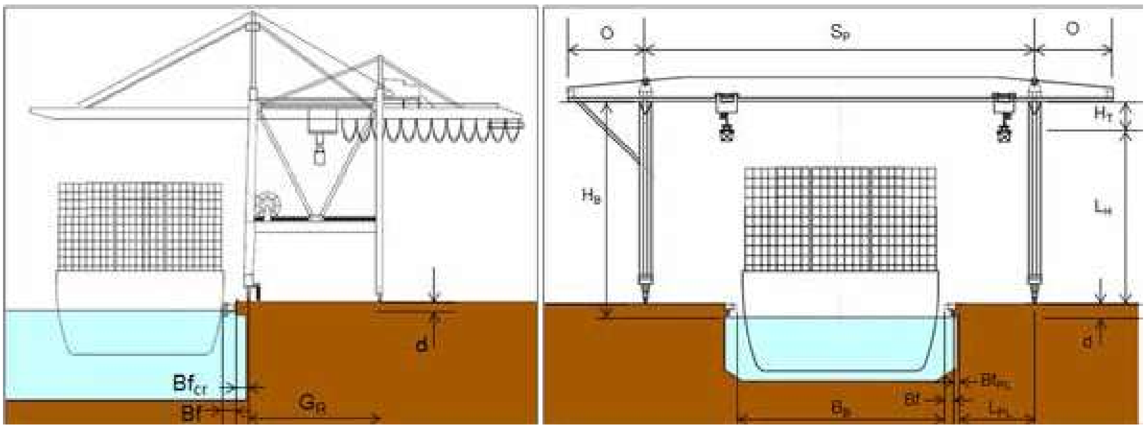

Figure 2: Geometric characteristics for SSG (left) and SSPC units (right).

Table 1: Typical geometric and technical characteristics of the SSG and SSPC concepts.

Characteristic	SSG	SSPC
Rail Gauge (G_R)	30.5 m	
Height of crane beam above sea level (H_B)		66.0 m
Height of trolley (H_T)		10.0 m
Vertical distance between sea level and quay (d)		5.0 mCD
Maximum lifting height of the crane above quay level (L_H)		51.0 m
Length of platform (L_{PL})		23.0 m
Buffer (Bf)	2.3 m	2.3 m
Distance between buffer and seaside rail of crane (Bf_{cr})	3.0 m	
Distance between buffer and platform (Bf_{PL})		3.0 m
Span (S_P)		130.6 m
Width of berth (B_B)		74.0 m
Hoist maximum speed, when spreader is unloaded (u_1)	180 m/min	180 m/min
Hoist maximum speed, when spreader is loaded (u_2)	90 m/min	90 m/min
Hoist acceleration or deceleration, unloaded or loaded ($\gamma_1=\gamma_2$)	0.75 m/s^2	0.75 m/s^2
Trolley maximum transit speed (u_3)	250 m/min	125 m/min
Trolley acceleration or deceleration (γ_3)	0.83 m/s^2	0.52 m/s^2
Gantry maximum travel speed (u_4)	45 m/min	30 m/min
Gantry acceleration or deceleration (γ_4)	0.15 m/s^2	0.09 m/s^2

Typical positions of SSPC units along a vessel are illustrated in Figure 3. Each arrow of each crane denotes the spanning beam.

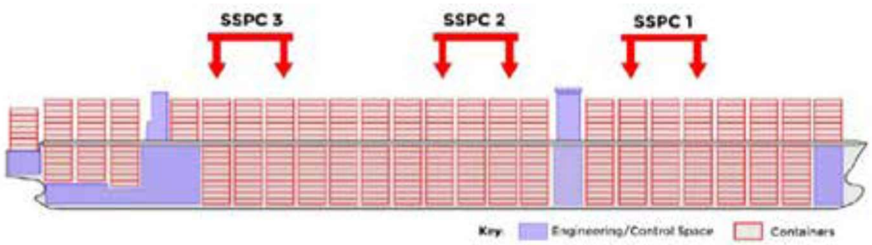

Figure 3: Typical positions of SSPC units along an ULCV.
Source: (Rankine et al. 2018)

Some basic benefits of the SSPC concept are:

- The loads on each runway are reduced and almost equal, due to the absence of the moment from the eccentric load on the SSG crane.
- The heavily loaded waterside crane rail can be located well behind the quay cope line, which leads to reduced berth construction costs and to the omission of the SSGs' heavy crane rail section. In addition, it protects the crane from being hit by a ship.
- There is no need for alteration of the port container handling vehicles, already used for the SSG concept.
- Port layout is more compact, due to the creation of a zone exclusively for transferring containers around the ship. The container terminal's vehicles cover shorter distances.
- The portal cranes can be deployed into existing terminals if indented berths are added, as well as included into plans for new ports (Figure 4). In the case of existing terminals, adding indented berths is costly, but there is a much-needed efficiency gained by it. More extensive research in this matter is required.

At this time, there is no port that has adopted this concept. However, there are communications for commercial implementation of the system in various Far East ports. The port modifications that should be made affect primarily the arrangement of the terminal. A typical indented berth would have the following characteristics:

- Length of the dock: 500 m (allowing 50 m for stem and stern mooring lines)
- Width of the dock: approx. 80 m (74 m clean space in order to accommodate 70 m wide vessels and 6 m for buffers or rotating wheel fenders)
- It is assumed that the vessels will always be accommodated in indented berths with the "bow in" method, in order to minimize the risk of damage in propellers and rudders, similar to the fendering and configuration of the Panama Canal lock entrances. Tug boats will be needed.
- Bunkering and provisions will be undertaken by stern or the dock edge.

Figure 4: Proposal for a terminal layout with two indented berths.
Source: (Rankine et al. 2018)

3. CALCULATIONS

3.1 DESCRIPTION OF THE STUDY

The aim in this section was to investigate quantitatively the reduction in port time for different ship designs and to determine how much that time was affected by the modification of the principal dimensions of the vessels. The study was conducted for a New-Panamax vessel with 14000 TEU (Case Study Vessel A – denoted as CSVA from this point forward) and for an ULCV of 20000 TEU (Case Study Vessel B – denoted as CSVB). The analysis focuses on modifications of the principal dimensions of the vessel without changing the ship TEU capacity.

Changes in the length, beam and depth for this type of vessels were made in terms of an integer multiple of bays, rows, and tiers, respectively. In order to exploit the advantages of the system, an increase of vessel beam was necessary. By increasing the beam and by keeping the TEU capacity of the vessels almost constant, the reduction of length and depth of the vessel were mandatory. For this reason, the modifications of vessels in the case studies were classified in three groups and in two sub-cases per group (see Table 2).

Table 2: Proposed cases.

Group	Case	Length	Beam	Depth
1	1.1	constant	+1 row	-1 tier
	1.2	constant	+2 rows	-2 tiers
2	2.1	-1 bay	+1 row	constant
	2.2	-2 bays	+2 rows	constant
3	3.1	-1 bay	+2 rows	-1 tier
	3.2	-2 bays	+4 rows	-2 tiers

Note: The bays were considered to be 40-feet long.

The first priority was to investigate the feasibility (seaworthiness) of all new cases and to calculate ship resistance; i.e. perform the so-called preliminary ship design. The preliminary design for all cases encompasses some general objectives, based on standard ship design theory. For the sake of simplicity, this procedure is not referred in this paper, however it is fully described in (Tsaganos 2020). In addition, a software tool for calculating cargo handling times was developed, in order to compare the cargo handling time efficiency of the various cases (Appendix A). The calculation of time was made for two different crane arrangements; (a) when six SSG cranes are deployed along the vessel and (b) when three SSPC units are deployed along the vessel. Finally, a techno-economic assessment for a typical voyage scenario was carried out.

3.2 CALCULATION OF CARGO HANDLING TIMES

An essential point of the study was to investigate whether vessels with the proposed designs enjoy any gains in port time. Quantification of the time gained was necessary in order to feed data to the techno-economic analysis that follows. The calculations have been incorporated in a specially developed software tool. However, the methodology is generic and can be applied to any vessel. In this section, a brief description of the methodology is depicted. More detailed analysis can be found in (Tsaganos 2020).

Some basic magnitudes of the vessel (vessel's beam, number of rows etc.) were necessary in order to determine the geometric size of each bay. The calculation of cargo handling times was based on the estimation of the cycle time in each bay. This is the time needed for the trolley to make one full move of operation (one full cycle). The developed software calculates cycle times separately for the TEUs located above and below deck in each bay. It treats both these groups of TEUs as a batch. For each batch, the position of the center of gravity (CoG) was calculated.

For the calculation of the cycle time, the desired trajectory of the hoist should be defined. There are two operations related to the cargo: loading and unloading. Each one of these two operations includes two phases of the crane hoist: ship-to-berth and berth-to-ship. For each phase, the sequence of the hoist movement consists of six points (or five stages) (Hamalainen et al 1995). The ship-to-berth trajectory for both concepts is depicted in Figure 5. The berth-to-ship phase follows an almost similar path; however, the trajectory points B to E are in different positions. The points' coordinates depend largely on the hoist speed and the acceleration time. These variables are differentiated by the trolley's loading condition (loaded with container or empty).

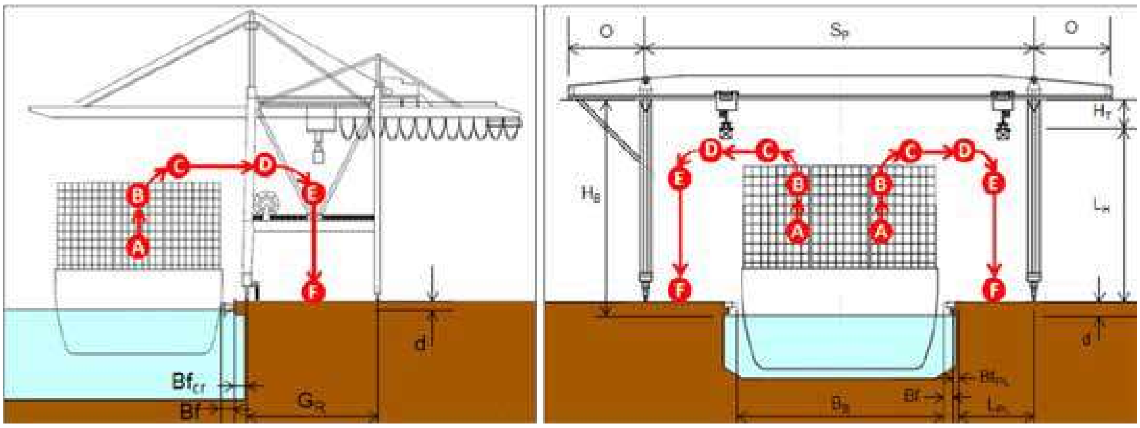

Figure 5: Ship-to-berth trajectory for SSG cranes (left) and SSPC unit (right).

Cycle time was defined as the sum of the times needed for the trolley to cover the distance between the trajectory points and the dwell time (assumed) for cargo handling in the port and on the ship. Initially, it was necessary to define the position of these points and, therefore, parametric equations were developed in order to calculate their coordinates. The idea of parametric equations originated from the necessity to apply the method to any ship. These equations were incorporated into the algorithm and depend on the following magnitudes:

- Beam at amidships
- Depth
- Double bottom height
- Height of hatch covers
- TEU transverse spacing
- Draughts at the beginning and at the end of operation
- Number of 20-feet bays
- Maximum number of container rows for both above and below deck
- Maximum number of container tiers for both above and below deck
- Transverse and vertical coordinates of bay center of gravity
- Width of berth (B_B) (only in SSPC concept)
- Container height
- Buffer (Bf)
- Vertical distance between sea and quay (d)
- Hoist maximum speeds (u_1, u_2)
- Trolley maximum transit speed (u_3) (different between the two crane concepts)
- Hoist acceleration/deceleration (γ_1=γ_2)
- Trolley acceleration/deceleration (γ_3) (different between crane concepts)
- Distance between buffer and seaside rail of crane (Bf_{cr}) (only in SSG concept)
- Distance between buffer and platform (Bf_{PL}) (only in SSPC concept)
- Rail Gauge (G_R) (only in SSG concept)
- Length of platform (L_{PL}) (only in SSPC concept)

The total operation time of a bay was calculated based on the cycle time and the capacity of each bay. However, the total operational time of the vessel depends on the number of deployed cranes along the ship. For either SSG or SSPC case, the crane operation plan was constructed. This defines which bays will be loaded/unloaded by each crane and in what sequence.

With the total operational time of each bay and the crane operational plan known, the total operational time of the vessel can be calculated. In the SSG concept, the crane operational plan was simple, since the SSG cranes operate in a single bay and therefore each crane loads/unloads a specific group of bays. The total operational time of each crane equals the sum of the total operational times of the bays serviced by this crane. The maximum of these values (i.e. of the operational times of each SSG crane) is the total operational time of the vessel. In the SSPC concept, the operational plan was more complex, because the SSPC units operate simultaneously at two non-adjacent bays.

3.3 TECHNO-ECONOMIC ASSESSMENT

The assessment was based on previous research (Zacharioudakis et al 2011), in which all parameters and formulae needed for the calculation of the costs of such vessels are described.

The cost function consists of port and ship related costs. Port related costs comprise cargo handling costs and fixed costs, such as port and canal fees. In ship related costs, fuel consumption in port and at sea, as well as other shipping costs, such as crew, maintenance, insurance and capital costs were included. If the ship is chartered, then another cost component, time charter cost, has to be considered (see Table 3).

Table 3: Dependence on cost parameters.

Cost type	Cost Component	Function of
Port related costs	Cargo handling cost	1) Cargo handling cost of each crane concept 2) Number of TEU loaded/unloaded at each port 3) System frequency – how frequently the roundtrips take place
	Fixed costs	1) Port fees 2) Canal fees
Ship related costs (owned vessels)	Fuel consumption costs in port	1) Fuel cost constant ($/t) 2) Daily fuel consumption of the ship in port (t/day) 3) Port time (based on TEU loaded/unloaded, system frequency, route length, idle time)
	Consumption cost at sea	1) Fuel cost constant ($/t) 2) Daily fuel consumption of the ship at sea 3) Sea time (based on route length and voyage speed (system frequency)
	Other variable cost (independent of voyage speed)	1) Crew cost 2) Maintenance cost 3) Insurance cost 4) Capital cost
Ship related costs (chartered vessels)	Time charter cost	1) Charter hire ($/day)

In order to calculate each cost component and for reasons of comparison between the various case studies, the construction of a voyage scenario, as the one below, was necessary:

1. The vessel departs from Shanghai fully loaded (100%).
2. Arrives in Felixstowe, where 50% of the cargo is unloaded, and it is loaded again with empty containers. Then the vessel departs for Rotterdam.
3. Arrives in Rotterdam, where the other 50% of the cargo is unloaded, and it is loaded again with empty containers. Then the vessel departs for Shanghai, fully loaded with empty containers.
4. Arrives in Shanghai, where 100% of the cargo is unloaded.

System frequency (how frequently the roundtrips take place) determines the speed of the vessel. For this reason, the ship was assumed to make a call at Shanghai every 56 days, resulting in 6.5 round trips per year. According to Zacharioudakis et al. (2011), an idle time of 10 hours per roundtrip of the vessel at port was taken into account.
Some cost components were assumed to either remain almost constant among the various ship cases, or their effect is negligible in the final result. These components can be considered as constant costs (C_{const}). Therefore, the aim was to calculate the rest of the cost components, i.e. the variable costs (C_{var}).

Terminal Handling Charges (THC) for each concept were needed to calculate the cargo handling costs. According to Rankine G. (2015), the SSG crane handling fee per move is considered to be 90$/TEU, whereas the corresponding SSPC handling fee was considered as 97$/TEU, due to the faster operations of the new system. According to our voyage scenario, the vessel is fully loaded and unloaded four times in each roundtrip. Therefore, the annual cargo handling cost is calculated as follows:

$$LU_{cost} = 4 \cdot TEU \cdot \left(\frac{Trips}{Year}\right) \cdot (Handling\,fee) \tag{1}$$

where TEU is the total TEU capacity of the vessel.
Fuel consumption, both in port and at sea, was based on main and auxiliary engines data. Essential factors of this calculation are port and sea time. Use of Very Low Sulphur Fuel Oil (VLSFO) and Low Sulphur Marine Gas Oil (LSMGO) was assumed, in order to comply with the Regulation for the "Sulphur Cap 2020" (MEPC.320(74) 2019). Typical fuel oil and lubricant oil prices are presented in Table 4.

Table 4: Fuel oil and lubricant oil prices (updated 29th December 2019).
Source: (LiveBunkers 2019)

Fuels	Rotterdam ($/ton)	Shanghai ($/ton)	Average ($/ton)
VLSFO	573.0	626.0	599.5
LSMGO	592.0	725.0	658.5
Cylinder Oil	4400.0	4400.0	4400.0
System Oil/Lubricant Oil	5180.0	5180.0	5180.0

The cargo handling costs and the consumption costs were summed up, resulting in the annual cost of the vessel.
Capital expenses were excluded from the calculations, due to lack of data and the fact that they do not significantly affect the results, since this is a comparative study among various ship design alternatives. According to literature (BRS Group 2020), most vessels of this type and size are operated by the shipowners (almost 60%). Therefore, chartering costs were also excluded from the calculations.
Port fees depend largely on the pricing policy of each terminal and their calculation is based on several factors, which cannot be determined at this stage. Hence, this cost component cannot be quantified and it was also not included in the final result. A qualitative assessment could be that the savings of the new system in port time proportionally affect the port fees.

4. RESULTS

The results of this study are presented below, following the procedures described in the previous sections.

4.1 CASE STUDY VESSEL A RESULTS

The CSVA is a 14000 TEU class vessel. The basic results obtained from the preliminary ship design procedure for all proposed configurations are depicted in Table 5. According to the preliminary ship design, all ship cases satisfied the stability and seaworthiness requirements (manoeuvrability, load line, EEDI). However, in some cases the stability index was very high;

this could be a major problem for this type of vessels since, apart from leading to possible parametric rolling, which it has to be taken into account when designing the bays and the lashing system.

Table 5: Preliminary ship design results for the CSVA cases.

Magnitudes	CSVA	Case 1.1	Case 1.2	Case 2.1	Case 2.2	Case 3.1	Case 3.2
TEU	14458	14492	14446	14456	14466	14522	14428
Length between perpendiculars (m)	353.0	353.0	353.0	338.3	323.7	338.3	323.7
Beam (m)	51.0	53.6	56.0	53.6	56.0	56.0	61.0
Depth (m)	29.9	27.3	24.7	29.9	29.9	27.3	24.7
Design Draught (m)	15.82	15.10	14.49	15.69	15.65	15.05	14.44
Shaft Horsepower @ 23 knots (kW)	49200	50511	51964	50671	52280	52034	54216

Table 6 presents results about the service speed, the performance (in terms of moves per hour), the time and cost savings calculated for each one of the above cases. The “Moves/hr” column shows the average moves per hour for either loading or unloading the whole vessel. According to the voyage scenario considered, a call at Shanghai is carried out every 56 days, thus the ship speed was accordingly calculated for each case. Shorter stay in port results in a longer sea voyage. This means that sailing in order to reach the destination by a predetermined date can be performed at a slower speed (and thus consumption). The percentage difference in port times with respect to the corresponding SSG design is presented in the “Time Savings” column. The percentage cost savings with respect to the corresponding SSG concept is presented in the last column.

Table 6: Time and techno-economic assessment's results for CSVA cases.

Ship	Crane Type	V (kn)	Moves per Hour	Time Savings (w.r.t. SSG) %	Time Savings (w.r.t. CSVA) %	Cost Savings (w.r.t. SSG) %
CSVA	SSG	19.9	253	-	-	-
	SSPC	18.3	419	32.7		3.6
Case 1.1	SSG	19.8	258	-	1.9	
	SSPC	18.4	429	29.4	-2.8	3.3
Case 1.2	SSG	19.7	263	-	4.3	-
	SSPC	18.1	445	33.5	5.4	4.1
Case 2.1	SSG	20.1	251	-	-5.0	-
	SSPC	18.6	419	29.2	-10.3	4.2
Case 2.2	SSG	20.3	249	-	-7.3	-
	SSPC	18.4	423	35.6	-2.7	6.2
Case 3.1	SSG	20.0	256	-	-3.2	-
	SSPC	18.3	434	33.6	-1.7	5.1
Case 3.2	SSG	19.8	268	-	0.6	-
	SSPC	18.1	463	37.4	7.6	5.7

Note: Negative sign (-) denotes increase of port time.

From the aforementioned results it can be confirmed that the use of SSPCs improves significantly the effectiveness of the cargo handling operations, reaching up to 463 moves per hour and increasing performance from 66 to 73% compared to the conventional SSGs, depending on the geometry of the vessel. This performance increase resulted in a significant reduction of the port time. The gain in time when using three SSPCs compared to the use of six conventional SSG cranes is in the range from 29 to 38%. As regards the comparison between the original CSVA and the alternative cases studied, only cases 1.2 and 3.2 resulted in a small port time reduction, whereas all others demanded more time for cargo handling.

According to the techno-economic assessment, the use of SSPCs slightly decreases the annual cost (up to 6%). The use of SSPCs reduces the ship consumption costs, but it increases the cargo handling costs, due to a difference of 7$ in the THC. As regards the comparison between the original CSVA and the studied alternative cases, the lowest annual cost is observed for the first. Moreover, by dividing the annual cost with the total number of TEUs/year, we arrive at an average cost for the transfer of one TEU which varies from 169 to 183 $/TEU. It should be reminded at this point that port fees are not included in our study and their consideration may significantly change the situation, since it is expected that they will be lower for the SSPC system, in a level proportional to the savings in port time (approx. 35%).

4.2 CASE STUDY VESSEL B RESULTS

The CSVB is a 20000 TEU class vessel. Table 7 shows the basic results obtained from the preliminary ship design procedure. According to the preliminary ship design, all ship cases satisfy the seaworthiness requirements (manoeuvrability, load line, EEDI). Stability analysis was not carried out due to lack of data for the original CSVB vessel, however no significant problems are expected. Moreover, it should be noted that the draught calculated from the preliminary ship design procedure for cases 2.2, 3.1 and 3.2 does not fulfil the current Suez Canal navigation requirements, regarding the permissible combinations of vessel beam and draught (Suez Canal Authority 2015). However, these cases were kept in the study for reason of completeness.

Table 7: Preliminary ship design results for the CSVB cases.

Magnitudes	CSVB	Case 1.1	Case 1.2	Case 2.1	Case 2.2	Case 3.1	Case 3.2
TEU	20000	20016	19916	19998	20030	20026	20074
Length between perpendiculars (m)	383.0	383.0	383.0	368.4	353.8	368.4	353.8
Beam (m)	58.8	61.3	63.8	61.3	63.8	63.8	68.8
Depth (m)	32.5	29.9	27.3	32.5	32.5	29.9	27.3
Design Draught (m)	16.03	15.42	14.85	15.96	15.92	15.37	14.84
Shaft Horsepower @ 23 knots (kW)	61530	62639	63890	62604	63643	63644	65590

Table 8 presents time and techno-economic assessment's results for each one of the above cases. To the best of the authors' knowledge, there are no existing SSG cranes that can load/unload vessels with a beam greater than 62m. Despite this fact and for the sake of completeness of this study, in cases 1.2, 2.2, 3.1 and 3.2 where vessels are assumed to be wider than 62m, existence of SSG cranes has been assumed. Table 8 has similar columns as Table 6.

Table 8: Time and techno-economic assessment's results for CSVB cases.

Ship	Crane Type	V (kn)	Moves per Hour	Time Savings (w.r.t. SSG) %	Time Savings (w.r.t. CSVB) %	Cost Savings (w.r.t. SSG) %
CSVB	SSG	22.4	239	-	-	-
	SSPC	19.6	412	33.8		8.6
Case 1.1	SSG	22.2	244	-	2.1	-
	SSPC	19.2	426	37.1	7.1	10.7
Case 1.2	SSG	22.0	249	-	4.6	-
	SSPC	19.3	437	34.4	5.5	9.6
Case 2.1	SSG	22.8	237	-	-3.9	-
	SSPC	19.3	416	39.5	5.1	13.0
Case 2.2	SSG	23.0	235	-	-5.9	-
	SSPC	19.7	416	35.6	-2.9	12.5
Case 3.1	SSG	22.6	242	-	-2.5	-
	SSPC	19.4	426	37.5	3.2	12.2
Case 3.2	SSG	22.4	245	-	-0.3	-
	SSPC	19.4	442	36.6	3.9	11.6

Note: Negative sign (-) denotes increase of port time.

From the aforementioned results it can be confirmed that the use of SSPCs improves significantly the effectiveness of the cargo handling operations, reaching up to 442 moves per hour and increasing performance from 72 to 82% compared to the conventional SSGs, depending on the geometry of the vessel. This performance increase resulted in a significant reduction of the port time. The gain in port time when using three SSPCs as compared to the use of six conventional SSG cranes is in the range from 34 to 40%. This reduction varies among cases and depends largely on the beam of the vessel. As regards the comparison between the original CSVB design and the studied alternative ones, some cases result in a small port time reduction, whereas some others in significant port time increase; the latter happening due to the very large increase of the beam of the vessel (e.g. case 3.2, see Table 2).

According to the techno-economic assessment, use of SSPCs significantly decreases the annual cost (up to 13%) compared to the use of SSGs. Consumption cost is reduced due to the lower required speed, however cargo handling cost slightly increases, due to a difference of 7$ in THC. As regards the comparison between the original CSVB design and the studied alternative cases, the situation is mixed. For some cases there is a slight reduction of the annual cost, however for some others there is significant increase, connected to the increased annual capacity of TEUs. The average cost for transferring one TEU in this case varies from 164 to 191 $/TEU, almost the same with the corresponding range for CSVA. Finally, it should be emphasized once more that the inclusion of the port fees in the above annual cost calculations may alter the situation, in a manner analogous to that for the CSVA concept.

5. CONCLUSIONS AND DISCUSSION

The basic conclusion that can safely be drawn from this research is that, compared to the conventional SSG cranes, use of SSPC units increases the cargo handling performance expressed through the number of moves per hour by up to 82% and reduces the port time by approx. 35% on the average. In addition, use of SSPC units leads to reduced service speed of the ships, hence the fuel consumption cost is reduced (by approx. 20% for the CSVA cases and 32% for the CSVB ones). However, the cargo handling cost increases, due to the assumed increased THC of the new concept cranes.

As regards the comparison of the annual costs of the use of the conventional SSG and the new concept SSPC units, the savings of the latter range are noteworthy, ranging from 3 to 13%. In actual figures, this saving is in the range from 2 million to 13 million dollars per year. Higher cost savings are achieved for CSVB cases. These savings may rise even higher, since the calculations carried out do not take into account the additional and likely savings in port fees when using SSPCs. The final outcome however will be basically determined by the pricing policy of the terminals.

This research also shows that the modification of the ship design by making the vessel wider and shorter and keeping the ship TEU capacity constant has a mixed outcome as regards port times; for some designs there is up to 8% saving in port time compared to the original ship design, whereas for some others there is up to 10% increase. A similar mixed result is also obtained when comparing the corresponding annual cost, which varies approx. from 3% saving to 4% increase. In addition to the above results, it should be noted here that by making the vessel wider and simultaneously reducing its draught, may provide to the vessel operator access to more ports around the globe that have shallow waters. Moreover, a wider ship means more TEU on deck, which are easier (and, hence, quicker) to load/unload.

As a general conclusion, assumptions by shipowners that larger vessels make the operations more efficient and economies of scale can be achieved (resulting in orders of larger vessels), are hereby confirmed.

The parametric cargo handling time calculation tool developed in this work can be used for further exploiting the effect of several other parameters that affect the final outcome of the study.

Future work could include a more detailed parametric analysis, by varying the main magnitudes that largely affect the effective and economically viable use of the new concept cranes, such as the implementation of additional cost components, the variation of assumed THC for SSPCs, the incorporation of other, more realistic voyage scenarios, etc. Moreover, a similar investigation can be carried out but from the terminal operator's point of view, based on the above data and results. The main question here is whether terminals can manage the faster rates of inbound and outbound containers and what changes need to be made to the whole terminal design and mode of operation. Finally, the development of a norm about keeping the longitudinal spacing between container bays constant for all new vessels would be very beneficial. This will lead to a better designation of the SSPC units (optimum distance of the crane main beams).

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APPENDIX A

"Description of the developed software tool"

A briefly description of the developed software tool for calculating loading/unloading times for the various cases is depicted below. The software is consisted of four features, which are included in the main menu (see Figure A.1).

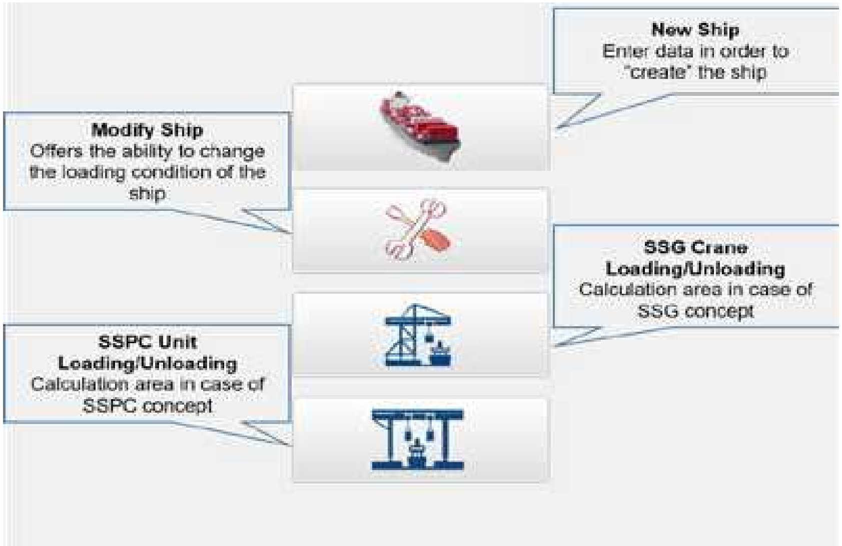

Figure A.1: Software's Main Menu

The features are listed and described below:

- "New Ship": This is the initial data entry process in order to incorporate the necessary magnitudes of the vessel into the algorithm. In the later stages of this feature, the user has the ability to upload manually the Bay Plan of the vessel (see Figure A.2). The software saves the information of each ship in its own database.

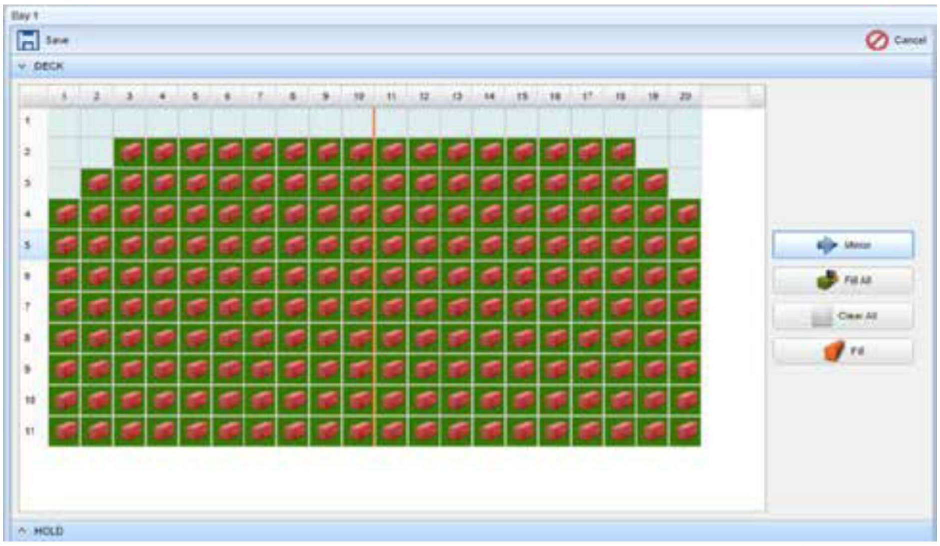

Figure A.2: Bay Plan window

- "Modify Ship": This feature offers the ability to the user to modify the loading condition of the vessel, by changing the Bay Plan that was incorporated in the first feature.
- "SSG / SSPC Unit Loading/Unloading" (last 2 features): In the last two features, the software opens the calculation area of the two different concepts studied. A short data entry process of the characteristics of each concept is needed. Then, the software runs the parametric equations referred to section 3.2, and calculates the results for each ship (see Figure A.3). These equations are incorporated into the algorithm and they are different for each concept. The tool has the ability to export the results of center of gravity of each bay, the cycle times of each bay and the total times of each bay, into an editable format (i.e. txt and csv format). The files are saved automatically as "results" in the software's directory.

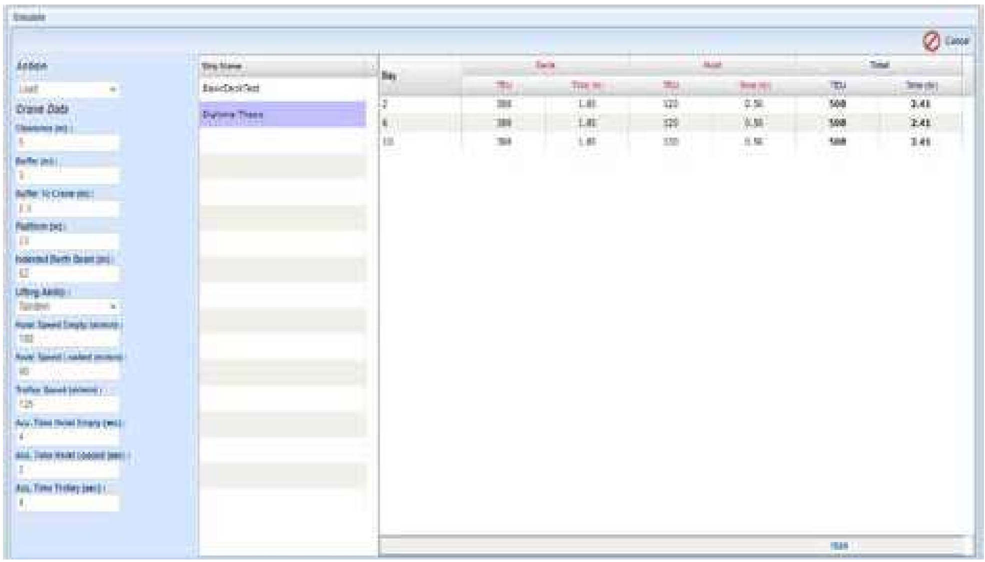

Figure A.3: Example of SSPC unit calculations feature.
(Left: Data entry area. Right: Results area)

*This description is not the "User's Manual" of the software. A detailed analysis and the "User's Manual" are depicted in (Tsaganos 2020).