CONTAINER MOVES PER LIFT: THE IMPACT OF SPREADER TECHNOLOGY ON BAY TIME

Shmuel Z. Yahalom(1)i, **Changqian Guan**(2) **and Elizabeth Langmaid**(1)

(1) Global Business and Transportation, State University of New York - Maritime College, New York, USA, syahalom@sunymaritime.edu

(2) United States Merchant Marine Academy, 300 Steamboat Road, Kings Point, New York, GuanC@USMMA.EDU

(3) Global Business and Transportation, State University of New York - Maritime College, New York, elangmaid@panynj.gov

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1. **ABSTRACT:** The trend of increasing containership size (length, beam, and draft) continues. The increase in containership size, especially beam size (bay size), increased berth and port time at a given number of lifts per hour. There are emerging technologies that allow a spreader of ship-to-shore gantry to handle multiple containers in a single lift. This paper studies the impact of the increase in the containership bay size on berth time and the role the spreader of gantry cranes can play in keeping up with the increase of bay size, thus reducing vessel port time. The paper analyzes the moves of containers per lift with different spreader technologies, where a spreader can handle one or multiple containers in one lift. The paper determines the combination of spreader technology needed to accommodate mega containerships with large bay sizes in order to reduce vessel port time. After a literature review, using the bay time determination method developed by the authors, the paper analyzes the moves per lift of different spreader technologies, vessel operations and containership bay size configurations. The analysis determines the optimal combination of equipment to comply with liner service schedules and the difficulties the equipment might pose on a marine container terminal.

2. INTRODUCTION

Containerships have been increasing in size. In 2017, OOCL launched five Triple-E[1] mega-containerships of 21,413 Twenty-foot Equivalent Units (TEU) each. For 2019, MSC and CMA CGM have on order twenty 22,000 TEU containerships. Currently, there are already sixty-six 18,000 TEU plus ships in service, and another forty-eight of 20,000 TEU plus are on order (Wikipedia, 2017). This phenomenon accentuates the continuing trend of increasing vessel size with projections of 24,000 TEU ships in 2020 (Sea Trade Maritime News, 2018).

The steady increase in orders of Triple-E class containerships is to take advantage of the economies of scale they provide at sea. As a result, pressure is rising on the ports to provide an appropriate productivity level that would discharge and load (D&L) mega-containerships quickly and efficiently within an allotted amount of time. The minimum amount of time it takes to D&L a containership depends on the containership bay size, the dominating factor of pier time, and the quay crane (QC) productivity (QC is also known as ship-to-shore container crane or gantry crane.). The larger the bay size, the more time it takes to D&L at a given QC productivity level (Yahalom and Guan, 2016). The increase in productivity levels of the QC has been very slow. The gap between the increase in QC productivity level and the increase in containership bay size is growing (Yahalom and Guan, 2017).

[1] "Triple E" is derived from "Economy of scale, Energy efficient and Environmentally improved".

Pressure mounts from carriers onto terminal operators as carriers request shorter stays at the port, and terminal operators need to improve the productivity rate in order to attract mega containerships. Currently, the QC productivity range is 25 to 38 lifts per hour. Through advancement in technology and terminal automation, the APM Terminal at Rotterdam has reached an average of 40 lifts per hour, the highest recorded in a port today (Port of Rotterdam, 2015). With respect to automation, shipping companies like Maersk are unconvinced that automation alone will increase lifts per hour as there has been no breakthrough yet that has resulted in 40 to 50 lifts per hour (Perina and Barrons, 2015). Furthermore, automation should also emphasize the increase in the number of containers moved per lift.

The quayside area of terminal operations is where port managers must invest to increase the productivity levels. The QC D&L process is the most important. QCs are limited by technology, but maximizing spreader capability would reduce the hours it takes to D&L a vessel bay. Currently, the maximum a spreader discharges is three 40ft containers or six 20ft containers per lift of the QC.

The paper discusses and demonstrates container moves per lift and their implications. A *lift* is defined as a QC spreader move to lift a single or multiple containers at once. A *move* is the number of containers a spreader can handle in one lift. For example, a spreader lifting and moving one container is a one-to-one ratio of move to lift. Whereas a spreader handling two 20ft containers and one 40ft container simultaneously would be a move-to-lift ratio of 3:1. Looking at various types of spreaders and technologies, the goal of terminal managers is to optimize spreader utilization in order to reduce the time it takes to D&L the largest bay, which is the dominating factor of pier time.

After the literature review, the methodology develops a move-to-lift ratio model given different spreader technologies in order to increase QC productivity for the largest bay at an allotted amount of time to complete the vessel operations. The conclusion identifies various spreader performances to minimize bay time, pier time and the constraints that may prohibit the QC productivity from reaching its potential.

3. LITERATURE REVIEW

The literature addressing QC performance focuses on container terminal quayside operation synchronized with the yard operation. In this respect there is indirect mentioning of quayside equipment. According to Diabat (2014), quayside is designated to allocate berths to arriving ships, and QCs are responsible for the D&L of the ships. The quality of the quayside equipment affects container throughput and handling efficiency, which in turn carries over into the yard operations. Jordan (2013) agrees with Diabat (2014) that QC productivity is a critical component of terminal productivity and may become the **limiting component** of terminal operations.

Quayside operation is the first part in managing a containership's berth time. There are several articles addressing quayside productivity, including berth and QC allocation and scheduling issues. Choo, et al (2010) analyze crane sequencing problems for multi-ships to minimize port stays using a heuristic approach based on a mixed-integer programming model. Hyongmo (2015) indicates that a mega containership should be in a container port for one day and altogether the QCs move 4,500 containers for the 18,000 TEU vessel class that is 80 percent of the quay utilization. Choo, et al (2010) look at yard congestion from high load and discharge activities.

As QC technology advances, researchers address the QC tandem lift. Choi, et al (2014) developed an operating system for the optimization of the container terminal by using tandem-lift QCs. Results show that as the tandem ratio increases, QC waiting time decreases, but yard crane waiting time increases due to an increase in quay activities. Chao and Lin (2011) studied tandem lifts for 40ft containers at Kaohsiung Port as alternates to single-lift QCs. Bartosek (2013) confirmed that QCs serve as one of the essential elements of the transshipment containers in a terminal. Yi, et al (2016) studied QC hoisting and concludes that the preference is "to use a single hoist dual spreader headblock at Yangshan Ports on the twin 40ft container QC."

Researchers study spreaders and tandem lifts. Bartosek (2013) looks at crane components and reveals future requirements for QC productivity. He and others also believe that tandem spreaders that can lift three

20ft containers or two 40ft containers are economical and more profitable. Lashkari, et al (2017) analyze the use of scheduling multi-spreader cranes that are capable of switching from multi-spreader to single-spreader modes. Huang, et al (2012) look at twinlift spreaders through a support vector machine-based fuzzy rules acquisition system.

The difficulties of implementing a multi-spreader approach deal with the variables of the stowing plan and yard congestion. Song (n.d.) looks at stow plans for each containership bay and the complexities in using multi-spreaders or single-spreaders depending on an odd or even number of rows in a bay. Choi, et al (2013) identify multiple capabilities of a spreader and how ship-to-yard vehicles must handle multiple containers in order to improve throughput of yard operations. Tierney, et al (2013) address optimizing multi-spreader productivity and stowage planning problems, while Delgado, et al (2012) describe a program that distributes containers to bay sections and slots.

The literature review did not find an explanation of spreader technology and its use in optimization of multi-lift spreader in the D&Ling of a container bay. Though articles were found regarding container stow plans, tandem QC scheduling, and multi-lift spreader use and their effects on yard congestion, no article has discussed the role of a spreader in closing the gap between bay size increase and QC productivity increase, which are the subject of this paper.

4. METHODOLOGY

Carriers seek a short and quick turnaround time in the port which is the time it takes to complete all the jobs between vessel's docking (berthing) and undocking (un-berthing). The dominating turnaround factor on board the containership is the bay size.

The methodology starts by describing the bay time principle that is based on the bay size and QC productivity and continues with a detailed description of several QC productivity issues, ratio of moves per lift and its critical technological components. The methodology completes with a determination of an effective productivity level and its associated technology that keeps a liner service on schedule.

4.1 Bay time

Bay time is defined as the amount of time it takes to D&L the largest fully loaded bay of a containership (Yahalom and Guan, 2016). From Yahalom and Guan (2017), "Containership bay time is determined by containership bay holding capacity (or size) (B_i) and quay crane productivity (lifts per hour) (P) (Yahalom and Guan, 2016). Since a bay is D&L'd, bay time is two times the time it takes to only discharge or load a bay, counting every container move separately and as one lift each (Equation 1).

$$B_{it} = \frac{2B_{ic}}{P} \qquad (1)$$

Where:

B_{it} is bay time (in hours).

B_{ic} is the number of containers (20ft and/or 40ft) in a bay, multiplied by 2 due to D&L.

P is quay crane productivity measured in container lifts per hour."

The time it takes to D&L a bay is a function of the bay size and QC productivity. The larger the bay, the more time it takes to complete D&Ling the entire bay and a vessel at a given QC productivity level (Yahalom and Guan, 2016, 2017). The larger the QC productivity, the less time it takes to completely D&L a bay, which is this paper's focus.

4.2 Productivity characteristics

The D&L bay time determination is complex. It depends on several QC operation variables, divided into four categories: D&L operations (together and separately), QC operator's skills, QC operation technology used and container terminal contracts with vessel owners/operators. Each of these categories impacts QC productivity differently. Equation 2 is a modification of equation 1, taking into account these characteristics as follows:

(2) $$B_{it} = \frac{BD_{ic}}{P.r.t.d} + \frac{BL_{ic}}{P.r.t.d}$$

Where:

$2B_{ic} = BD_{ic} + BL_{ic}$ is the number of containers (20ft and/or 40ft) D&L'd in a bay. The D&L operation is separated to discharge (D) and load (L).

P is quay crane productivity measured in container *lifts per hour*.

r is the ***ratio*** of the average number of containers *moved per lift.*

t is a *coefficient of utilization* of the theoretical productivity.

d is a *coefficient* of *dual cycle,* taking into account dual cycle operations productivity.

Bay time could be subject to all or some of the variables identified in equation 2. Several of the variables are self-explanatory.

The moves-per-lift ratio (r) is a QC productivity measure indicating the theoretical average number of containers *moved per lift* (Equations 2 and 3). The ratio is the basis for determining the needs for performance enhancement.

(3) $$r = \frac{M\ (Number\ of\ containers)}{L\ \ (one\ lift)}$$

A ***lift*** (L) is defined as a simple QC spreader pickup of a container(s) to discharge or load. For example, a lift could be one container or a block of six containers. In either case, it is one lift. A ***move*** (M) is the number of containers a spreader can handle (move) in one lift. From the aforementioned, for a lift of one container, M = 1, and for a lift of six containers, M = 6. The r's average ratio in equation 2 is one or larger (r ≥ 1).

- r = 1 is the most common operation of moving one container at a time. Historically, for a containership with a small number of D&Ls, one lift is equal to one move (L = M). This operation is usually with a spreader designed to move a single container, which is also the operation's *baseline*.
- r > 1 is an operation based on moving multiple containers per lift. This measure is applied to dual cycling and advanced spreader technology.

The *coefficient of utilization* (*t*) addresses the deficiencies of QC multi-container D&L operations due to technologies such as twinlift, triple-lift, quatro-lift, hexa-lift (six) and their combinations. A multi-container operation takes more time to lock containers to both the spreader on board a vessel and quay when placing containers on a flatbed, compared to a single container D&L operation. The added time is due to technology adjustment, sometimes per lift, and slower hoisting and trolling of the D&L operation. Since the moves per lift (r) are theoretically associated with the spreader technology (twinlift: r =2, triple-lift: r = 3, and quatro-lift: r = 4), the operating productivity t is reported at 70 percent of the one-container-per-lift operation. This average coefficient could also include the occasional system failure time (Bartosek and Marek, 2013). Furthermore, one can also expect a non-linear relation of the coefficient of utilization; with an increase in r, the utilization could be smaller, for example, when r = 4, t = 65 percent.

The *Coefficient of dual cycle* (*d*) operation refers to a QC moving two containers in each cycle, discharging an import container and loading an export container on the return trip to pick up the next import container. A dual cycle operation, which is feasible only below deck and not for all tiers, turns an empty trolley crane move into a more productive move, doubling the number of containers moved in one cycle. Through their research Goodchild and Daganzo (2006, 2007) demonstrate that QC dual-cycle productivity can increase overall D&L operations by 10 percent.

The pressure on terminal operators to move multiple containers is common in large or busy marine container terminals. The pressure is driven by competition and turnaround time specifications in the contracts, especially when vessels are large and the existing technology is inadequate to complete the D&L operation on time. However, the multiple container moving operation has its limits because, presently, it is feasible only for (1) dual cycle operation below deck and for (2) twinlift operation when discharging a bay. Therefore, what is a sufficient r for completing a bay on time?

5. BAY SIZE AND QC PERFORMANCE

Bay size determines the number of containers for D&L in a containership. The larger the bay, the more containers are stored and moved. Frequently a bay is separated by a hatch cover between the above and below decks. For example, a Triple E containership's largest bay could store above deck 230 40ft containers (23 rows x 10 tiers) and below deck 174 40ft containers (22 rows x 8 tiers - 2) or a total of 404 40ft containers. Other Triple Es design the largest bay with 396 40ft containers. For subsequent illustrations a bay size of 396 40ft containers is used.

The evolution of bay size increase and QC productivity increase (lifts per hour) over the last 20 years is not synchronized. For example, the increase in containership bay size since the launching of the Panamax vessel class some 20 years ago was 202 percent (from the Panamax's 131 40ft containers per bay to the Triple E's with 396 40ft containers per bay). The increase in QC single lifts per hour in the last 20 years was 90 percent (from 20 to 38 lifts per hour). These two trends resulted in a gap between them of 112 percent (Yahalom and Guan, 2017 and Figure 1 reproduced from the study). The persistent gap is recognized by the industry which is challenging terminal operators to handle 6,000 containers in a 24-hour period (van Marle, 2015).

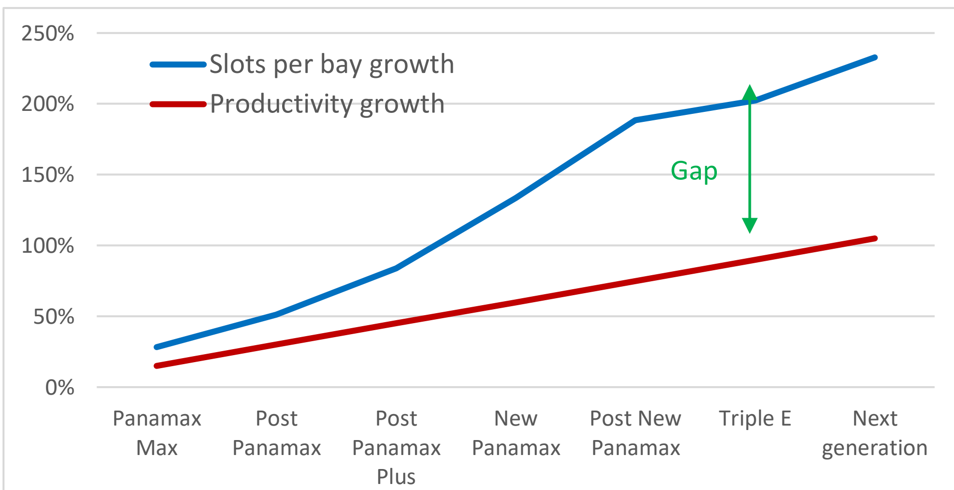

Figure 1: Slots per Bay Growth and Productivity Growth

The gap can be closed by using a combination of an increase in each of the QC operation alternatives such as: lift per hour, dual cycling, various advanced spreader technologies, Fastnet technology (on the drawing board) and others (Soderberg, et al, 2016). Management tools that increase productivity include sophisticated computer programs for interface handling of containers between the quay and the yard, including stowing plans, plans for dual cycling, sophisticated spreaders automation features and pick-up by appointment. In short, in the effort to improve efficiency and productivity, the container terminal management has to overcome many obstacles and challenges, some of which are costly technologies.

6. GAP ANALYSIS

Closing the gap between bay size increase and QC lifts per hour increase (Figure 1) is effective productivity. *Effective productivity* is defined as the number of *moves per hour*, which close the gap created by the increase in the containership's largest bay size in order to complete a bay at an allotted amount of time. Obviously, containerships of different bay sizes require a different number of moves per hour using a mix of D&L tools identified above.

- Assuming an allotted 20 hours to complete the largest bay (Table 2), an analysis of the different vessel classes indicate that the Triple E requires a minimum of 39.60 lifts per hour (792/20) to D&L the largest bay of 40ft containers. A mixed bay of 20ft (40 percent) and 40ft (60 percent) containers requires 55.44 lifts per hour (1,109/20).

- Assuming a QC average of 35 lifts an hour (Table 1), the D&L of the largest bay of 40ft containers of a Triple E takes a minimum of 22.63 hours to complete. Furthermore, every increase in vessel class added 36 to 144 containers (88 average) and 1.03 to 4.11 hours (2.5 average) to the D&L time (from Table 1). The D&L of the largest mixed container bay (20ft and 40ft) for the New Panamax, Post New Panamax and the Triple E vessel class, takes more than 20 hours to complete. As before, an increase in vessel class added 51 to 201 containers (124 average) and 1.46 to 5.74 hours (3.5 average) to the D&L time (from Table 1).

In short, both cases indicate that the number of moves per lift is larger than one (r > 1), where the total time to D&L a 40ft bay is less than 20 hours.

Table 1.Lifts per hour required to D&L a containership in 20 hours and the number of hours required to D&L the largest bay at 38 lifts per hour

	40ft container			Mix of 40% 20ft and 60% 40ft containers		
Vessel class	Number of containers for D&L	Minimum lifts per hour in 20 hrs	Minimum number of hours with 35 lifts per hour	Number of containers for D&L	Minimum lifts per hour in 20 hrs	Minimum number of hours with 35 lifts per hour
Panamax	262	13.10	7.49	367	18.34	10.48
Panamax Max	336	16.80	9.60	470	23.52	13.44
Post Panamax	396	19.80	11.31	554	27.72	15.84
Post Panamax Plus	482	24.10	13.77	675	33.74	19.28
New Panamax	612	30.60	17.49	857	42.84	24.48
Post New Panamax	756	37.80	21.60	1,058	52.92	30.24
Triple E	792	**39.60**	**22.63**	1,109	**55.44**	**31.68**

A 10 percent increase in productivity due to dual cycling closes the gap for the Triple E bay of 40ft containers (35 x 1.10 = 38.5 moves per hour where the required average lifts per hour is only 39.6). But the 10 percent increase in productivity of dual cycling is still inadequate in closing the gap for the mixed container bays for the New Panamax, Post New Panamax and the Triple E vessel class (Table 1).

Multiple container moves with every QC lift, such as twinlift spreader technology (tandem or abreast), would close the gap. For example, the potential number of container moves of a twinlift spreader handling two containers in every lift (r = 2) at an average rate of 35 lifts per hour, in 20 hours is 1,400 containers (2 x 35 x 20). Therefore, the Triple E mixed bay of 1,109 containers requires that 79 percent (1,109/1,400) of its containers be D&L by twinlift spreaders to complete the largest bay on time (Twin lifting the entire bay takes 15.84 hours = 1,109/(2 x 35)) (Table 2 and Figure 3). Obviously, the smaller the number of average lifts per hour, the larger the number of twinlift operations required. However, at 70 percent twinlift operation efficiency, the potential number of containers moved in 20 hours is only 980 (1,400 x 0.70), which indicates that the entire bay should be a twinlift operation.

Table 2 and figures 2 and 3 illustrate the performance outcomes of various lifts per hour. They indicate that a vessel's QC D&L operation at a low lifts per hour rate with twinlift spreaders always generate higher moves per hour. The benefits of using twinlift spreaders are especially important when the ratio of twinlift operations is larger than 0.50. Because a 0.50 twinlift operation is equivalent to the baseline of r = 1 operation with a single spreader of one container per lift, which is also the minimum required operation ratio to stay on time.

Table 2. Twinlift D&L operation ratio in order to complete the largest bay in 20 hours

Vessel class	40ft containers (lifts per hour)					Mixed 20ft and 40ft containers* (lifts per hour)				
	Number of containers	30	35	38	40	Number of containers	30	35	38	40
Panamax	262	0.22	0.19	0.17	0.16	367	0.31	0.26	0.24	0.23
Panamax Max	336	0.28	0.24	0.22	0.21	470	0.39	0.34	0.31	0.29
Post Panamax	396	0.33	0.28	0.26	0.25	554	0.46	0.40	0.36	0.35
Post Panamax Plus	482	0.40	0.34	0.32	0.30	675	0.56	0.48	0.44	0.42
New Panamax	612	0.51	0.44	0.40	0.38	857	0.71	0.61	0.56	0.54
Post New Panamax	756	0.63	0.54	0.50	0.47	1,058	0.88	0.76	0.70	0.66
Triple E	792	0.66	0.57	0.52	0.50	1,109	**0.92**	**0.79**	**0.73**	**0.69**

*40% of 20ft and 60% of 40ft containers

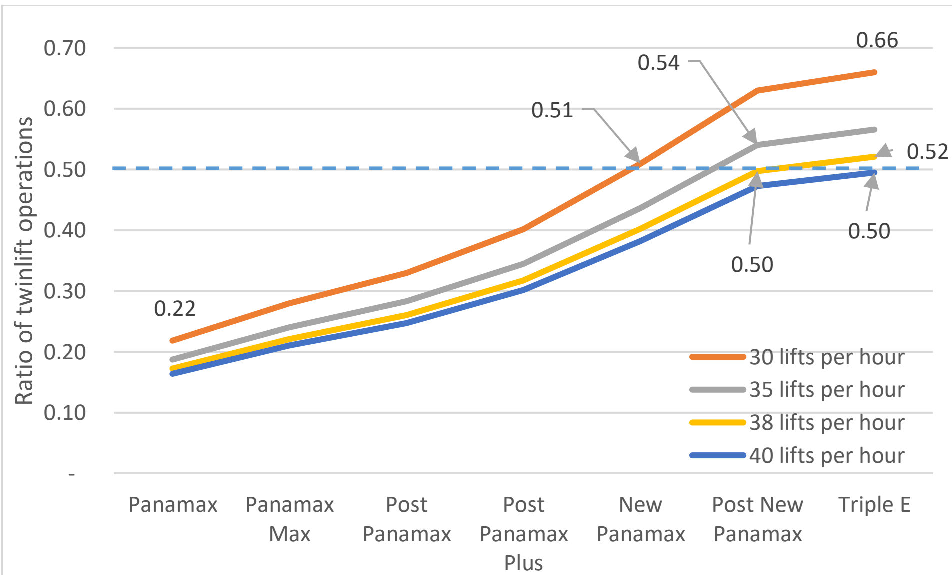

Figure 2: Twinlift Operation Ratios for a 40ft Container Bay

The ratios of QC twinlift D&L operations of the largest bay of 40ft containers at different lifts per hour (Table 2 and Figure 2) indicate that the Triple E equals one container per lift only at 40 lifts per hour rate (0.50). The others fall behind and require exstensive twinlift operations.

A D&L operation of a mixed bay of 20ft and 40ft containers requires twinlifts to be completed in 20 hours. For instance, the Triple E at 30 lifts per hour requires that 92 percent [1,109/(30 x 20 x 2)] of the QC operation be twinlift. A QC with 40 lifts per hour requires a twinlift of only 69 percent of the operation (Table 2 and Figure 3). In short, four classes of vessels require twinlift operations in an allotted 20 hours.

A twinlift operation could handle a maximum of four 20ft containers (tandem and abreast). Applying this number of moves per lift (r = 4) reduces the time even further. Clearly, a three 40ft container operation and its combinations (tandem and abreast) will complete D&Ling a bay faster than one container per lift. Still, a dual lift D&L operation (d = 0.10) at 70 percent capacity (t = 0.70) would be slower (Table 1).

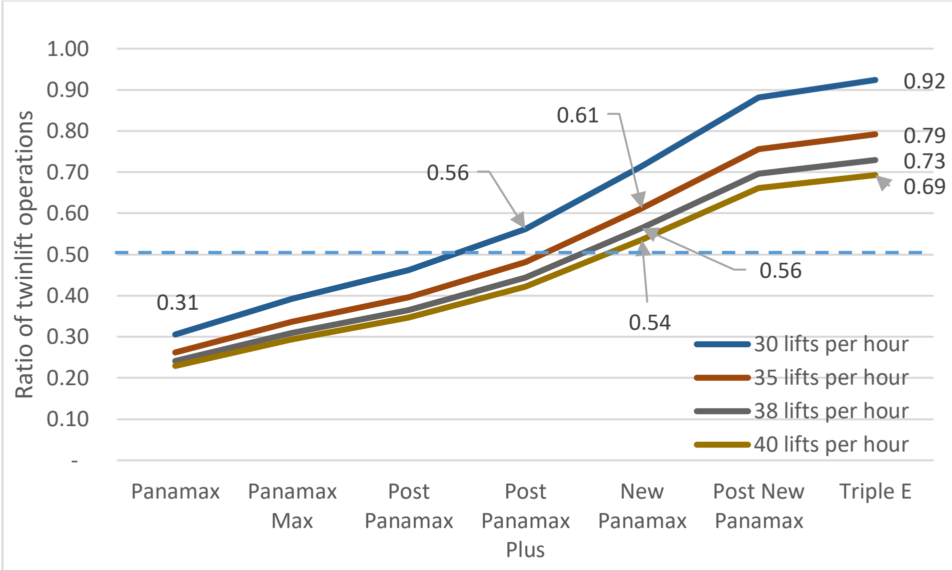

Figure 3: Twinlift Operation Ratios for a Mixed Bay of 20ft and 40ft Containers

Bay time also depends on the number of bays blocked by a QC. As indicated before, with the existing technology the standard QC physically blocks two bays. Therefore, when a QC serves two adjacent bays, it takes double the amount of time it takes to D&L one bay in anyone of the outlined scenarios above.

7. PRODUCTIVITY IMPROVEMENT ALTERNATIVES AND ILLUSTRATIONS

Containership D&L operation's schedule is based on QC productivity. The larger the productivity, the shorter the bay time, berth time and port time. In order to be competitive, container port managers improve productivity by resorting to a combination of managerial tools and technologies.

Equation 2 illustrates the inverse relationship between QC productivity and bay time. Bay size (B_{ic}) is constant per vessel and frequently within vessel class. Therefore, a container terminal with a contractual obligation to complete a containership within a given amount of time (hereinafter bay time of 20 hours) must increase it QC productivity (*P and r*) as the vessel's bay size increases with the deployment of wider containerships. For example, the Triple E containership with 396 40ft containers in the largest bay increased from the 378 40ft containers in the largest bay of the Post New Panamax containership vessel class. Thus, in order for a container terminal to fully D&L the Triple E new bay size and maintain a 20 hour bay time, the productivity level had to increase from an average of 37.8 (378 x 2/20) moves per hour to an average of 39.6 (396 x 2/20) moves per hour. The average two additional moves per hour can be achieved in multiple ways frequently by spreader technology that determines how many containers a spreader moves in one lift. Advanced spreader technology moves multiple containers in one lift. Using equation 2, r takes various values depending on spreader and operation technologies.

7.1 Single lift operation (baseline)

Container operations start with a single container lift. The simplest D&L operation is to lift one container at a time (import or discharge container) and return the spreader empty for the next discharge. In terms of equation 2, r = 1, assuming t = 1 and d = 1, therefore, $B_{it} = 2B_{ic} / P$.

Presently the global range of D&Ling operations of a single lift per hour is between 33 and 38. For instance, a single lift operation of D&L of a bay of 792 40ft (396 x 2) containers at a productivity level of 35 lifts per hour takes 22.6 hours (792/35). Furthermore, since a standard QC blocks two bays, it takes 45.2 hours to complete two adjacent bays.

Bays are frequently stacked with a mix of 20ft and 40ft containers. Therefore, the amount of time it takes to D&L a mixed bay is larger. For instance, a split bay with 40 percent of 20ft containers and 60 percent of 40ft containers takes 31.7 hours to D&L [(792 x 0.4) x 2 + (792 x 0.6) = 1,109/35] or 63.4 hours for two adjacent bays, an additional 40 percent compared to a bay with the same size containers.

Ports that require safety margin and/or interference avoidance in their operation add space between QCs that blocks additional bays (OECD/ITF, 2015) and requires additional time to complete adjacent bays. One and two additional bay blockages increase bay time to 67.8 hours and 95 hours, respectively, in the two aforementioned examples. Furthermore, Hyongmo (2015) calculates that the maximum number of QCs per containership should be one QC per about 50 meters (164ft) of the vessel's length (LOA), thereby blocking four bays. Reaffirming this ratio is the practice of deploying eight QCs per 400 meters of the vessel's length and, again, the perception that vessel length is the dominating factor (van Marle, 2015) where actually the vessel's beam is the dominating factor, not the vessel's length, in determining bay time and berth time (Yahalom and Guan, 2016, 2017).

The large amount of time it takes to D&L wide containerships is not competitive and not acceptable to the container port customers. QC developers seek to increase QC productivity in order to reduce bay time and consequently berth time and port time.

7.2 Single lift and dual cycle operation

The most economical method (operating with existing equipment and a sophisticated crane/yard operating system) to increase QC productivity and reduce the bay time gap is by using a dual cycle operation (Goodchild 2005; Goodchild and Daganzo 2006; Goodchild and Daganzo 2007; World Caro News 2007; Zhang and Kim 2009; also called "dual command cycle operation" by Kim and Lee, 2015). Testing dual cycling confirmed a 10 percent productivity improvement and in one instance a 30 percent improvement (World Caro News 2007). In terms of equation 2, d = 1.10, r = 1 and t = 1 or 0.70.

For example, applying the 10 percent productivity increase due to dual cycling (d = 1.10, r = 1 and t = 1) to the two aforementioned, reduces the bay time from 22.63 hours to 20.57 hours [792/(1.1*35)] for the same container size per bay and from 31.7 hours to 28.8 hours [1,109/(1.1*35)] for a mixed containers per bay of 20ft and 40ft, respectively. Furthermore, since dual cycling productivity improvements are for the entire operation, the aforementioned figures are not subject to utilization constraints (t) of 70 percent. However, given the large gap indicated above (Figure 1), dual cycling is not enough to close the indicated gap.

7.3 Advanced spreader technology

Advanced spreader technology, increases QC productivity, are spreaders that discharge multiple containers in one lift abreast (side-by-side) and/or in tandem (one-after-another). At the present time, due to technological limitations, multiple container moves are <u>only for discharge operations</u>. We expect future multiple container moves for load as well. Multiple containers per lift include: a *twinlift* (tandem, abreast or vertical, also called Vertical Tandem Lift - VTL), *triple spreader* (three-lift in various abreast and tandem combinations), *quadruple lift* (in various abreast and tandem combinations), *BLOK-BEAM* spreader technology handles six empty containers in a block of three horizontally and three more below (r = 6) (Louppova, 2016; MAREX 2016), *SINGA Port* (Jiang, et al 2015) envisions an operation with a "triple hoist quay crane with tandem lift. The quay crane can achieve 38 moves per hour and move 152 TEUs per hour" and others (Lind, et al 2007; ZPMC n.d.; Louppova 2016; MAREX 2016). Hay (2016) reports 60 containers move per hour.

7.4 Multiple lift operation

The most common multiple container lift used is the twinlift abreast (twin-40). Twinlift spreaders increase efficiency and versatility. A twinlift spreader can discharge four TEUs per cycle (two 40ft containers abreast, four 20ft containers abreast, tandem or 12 containers abreast, tandem combinations) with a single set of controls and operator (Johansen, 2007).

Many container terminals separate the discharge and load of a twinlift operation. After the discharge operation is completed, the load operation starts. In terms of equation 2, presently: the *discharge* rate could be r = 2, 3 or 4. The *load* operation is one container per lift, r = 1 (assuming d = 1 and t = 1).

For instance, assuming a flawless operation (d = 1 and t = 1) of a twinlift 40ft spreader that fully discharges a Triple E bay by lifting in every discharge two 40ft containers (r = 2) and loading one container at a time at 35 lift per hour, it takes 16.97 hours [396/(2 x 35) + 396/35] to complete D&Ling of a bay of 396 40ft containers; discharge of r = 3 takes 15.09 hours and for r = 4 it takes 14.14 hours (Table 3, line 3). Thus, effectively, the overall multiple discharge operation reduces the total number of trolley trips ratio to r = 1.5, 1.33 and 1.25, respectively (Table 3, line 6). A QC operation of two adjacent bays will double these figures.

The probability of a flawless multi spreader operation throughout the entire bay (t = 1) is very small; therefore, the actual amount of time to D&L a bay of 40ft containers is larger. At an operating productivity of 70 percent (t = 0.70), the aforementioned will be 24.24 (16.97 x 1/0.70), 21.54 and 20.2 hours, respectively (Table 3, line 4). However, with dual cycle (d = 0.10) the number of hours decline to 22.04 (24.24/1.1), 19.59 and 18.37, respectively (Table 3, line 4a). A mixed bay at 70 percent efficiency will generate bay time of 30.87, 27.45 and 25.73 hours, respectively (Table 3, line 4a). Applying this methodology to all vessel classes indicates that presently a bay with 40ft containers of the Post New Panamax and the Triple E will take more than 20 hours to D&L with twinlifts of 35 lifts per hour but triple and quatro lifts will put the bay time operation below 20 hours (Figure 4).

Table 3. The number of hours to D&L a Triple E containership using multiple lift operation

Activity	**# of Boxes**	**Container size 40ft**				**# of Boxes**	**20ft and 40ft**			
		Spreader technology					**Spreader technology**			
		Single lift	**Twin-lift**	**Triple-lift**	**Quatro-lift**		**Single lift**	**Twin-lift**	**Triple-lift**	**Quatro-lift**
Design moves per lift (r)		**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**
Present										
1. **Discharge** time (multiple lifts)	396	11.31	5.66	3.77	2.83	555	15.86	7.93	5.29	3.96
2. **Load** time (single lift)	396	11.31	11.31	11.31	11.31	554	15.83	15.83	15.83	15.83
3. Total Time (hours)	792	**22.63**	**16.97**	**15.09**	**14.14**	1109	**31.69**	**23.76**	**21.11**	**19.79**
4. Coefficient of utilization (t=0.70) hours		**NA**	**24.24**	**21.55**	**20.20**		**NA**	**33.94**	**30.16**	**28.28**
4a. (d=0.10) + (t=0.70) hours			**22.04**	**19.59**	**18.37**			**30.85**	**27.42**	**25.71**
5. Ratio of multiple lift to single lift		1	0.75	0.67	0.63		1	0.75	0.67	0.62
6. Actual number of trolley trips (r)	792	2	1.5	1.33	1.25	1109	2	1.50	1.33	1.25
Future										
7. Future D&L time	792	**22.63**	**11.31**	**7.54**	**5.66**	1109	**31.69**	**15.84**	**10.56**	**7.92**
8. Ratio of multiple lift to single lift		1	0.50	0.33	0.25		1	0.50	0.33	0.25
9. Dual-cycle coefficient (d=0.10)	792	20.57	10.78	7.30	5.52	1109	28.81	15.09	10.22	7.73
10. Coefficient of utilization (t=0.70)	792	NA	16.16	10.78	8.08	1109	NA	22.63	15.09	11.32
11. (d=0.10) + (t=0.70)	792	NA	15.39	10.43	7.88	1109	NA	21.55	14.60	11.04

Similarly, a mixed bay of 20ft and 40ft containers will presently take more time to D&L at the same conditions. At mixed bay dual cycle operations at 35 lifts per hour and 70 percent productivity, even at a quatro lift, is not enough to obtain a bay time of 20 hours. The vessels class that are affected include the Post Panamax, New Panamax, Post New Panamax and the Triple E (Figure 5).

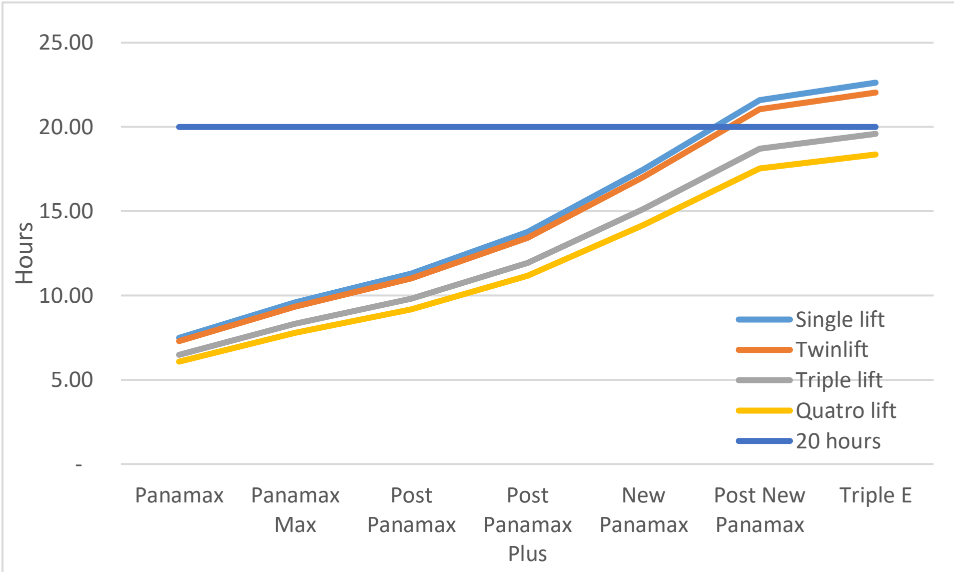

Figure 4: Present D&L Time of 40ft Container Bays at 35 Lifts per Hour Dual Cycle and 70 Percent Productivity

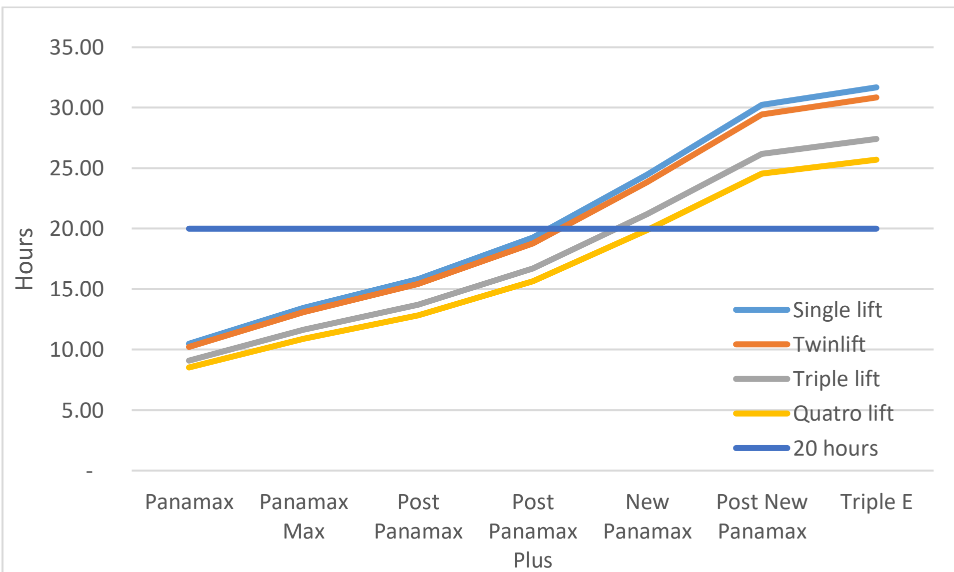

Figure 5: Present D&L Time of Mixed Container Bay at 35 Lifts per Hour Dual Cycle and 70 Percent Productivity

The future aforementioned advanced twinlift spreader operation is expected to be of multiple containers in every D&L.

- In terms of equation 2, r = 2, 3, and 4, d = 1 and t = 1. The operation times are 11.31, 7.54 and 5.66 hours respectively and the overall operation is reduced by 1/2, 1/3, and 1/4, respectively (Table 3, lines 7 and 8), which is time efficient compared to the contemporary operation system.
- Advanced spreader technology and dual cycle operation provide additional operation efficiencies. In terms of equation 2, assuming d = 0.10, the r's are: twinlift r = 2.1, triple lift r = 3.1 and quadruple lift

r = 4.1. The corresponding amounts of time to D&L a 396 container bay are 10.78, 7.30 and 5.52 hours, respectively (Table 3, line 9).

- But, with a likelihood of only 70 percent operation efficiency (t = 0.70), the aforementioned figures are 16.16 (11.31 x 1/0.70), 10.78 and 8.08 hours, respectively (Table 3, line 10).
- Finally, the aforementioned with dual cycling (d = 0.10) and partial utilization (t = 0.70) the operation takes 15.39, 10.43 and 7.88 hours, respectively (Table 3, line 11).

The future D&L operation, by fully twin-lifting a bay, is expected to be achieved in stages starting a full twinlift below deck before reaching a total twinlift operation.

The number of twinlift spreader operations of QC trips depends also on the mix of 20ft and 40ft containers in a bay. The twinlift technology is versatile and could lift 12 combinations of 20ft and 40ft container configuration. Table 3 illustrates the time it takes to D&L a Triple E bay of 396 mixed containers of 40 percent 20ft containers and 60 percent 40ft containers. The illustration is parallel to the 40ft container case. The comparison highlights that it takes 40 percent more time to D&L a mixed bay across the board when compared to a single bay D&L operation. However, it also indicates that twinlift and triple lift in every lift will close the gap and keep a bay time D&L operation at 20 hours or less.

8. CONCLUSIONS AND RECOMMENDATIONS

Completing D&Ling the largest bay, which is the dominating factor, of very large containerships in an allotted amount of time is a container's port industry challenge. The gap between containership bay size growth and QC lifts per hour growth is growing with every launch of a new containership class.

The gap is recognized by the port industry and its technology providers. Multiple solutions and tools were developed to D&L the largest bay in order to increase QC moves per hour that will keep a containership at the port for the minimum amount of time.

This paper has developed an *effective productivity* concept that calculates the number of moves per hour needed to complete D&Ling the largest bay on time using multiple D&L technologies and operation processes. Since every container terminal and containership are different, it is not possible to prescribe a uniform solution to close the gap. Every terminal is designed differently and uses different equipment, the equipment operators have different skills, and the contractual agreement addresses allotted time differently. However, within the variety of solutions presently available, advanced spreader technology and dual cycling, in this order, dominate.

Presently, due to operation limitations and technological and operations constraints, the QC operations, on very large containerships, are not able to comply with the contractual allotted time. The paper demonstrates that a mixed bay of 20ft and 40ft containers in large containerships (Post Panamax Plus, New Panamax, Post New Panamax and Triple E) takes more than 20 hours to D&L the largest bay using a single lift operation, and that with every increase in containership class the average number of hours of D&L increased by 3.5 hours. Multiple spreader operation at 70 percent productivity and dual cycling improve performance, but it does not close the gap. As a result, containerships are delayed and shipping lines call multiple ports in a voyage.

In the future, container terminals are expected to gradually accommodate the vessels by overcoming the present limitations and constraints associated with the vessel (no hatch) and container yard operations (a QC per bay). Other expected improvements in the D&L operations include: an increase in the number of lifts per hour from 38 to 50 per hour, an increase in spreader operations efficiency from 70 to 90 percent and an increase in dual cycling efficiency from 10 to 50 percent. These performance improvements require investments in advanced spreaders capable of multiple container lifts, invest in new QC per bay technology (such as "Fastnet"), monitor system operations to increase dual cycling, and overall improve operations synchronization. These measures will increase the move-to-lift ratio and vessel turnaround time quicker.

Future research should concentrate on accommodations' challenges of new technologies such as spreaders, vessel design (especially beam size), methods to close the operations gap (operation systems analysis and synchronization analysis), and the determination of the right mix of equipment.

9. REFERENCES

1. Bartosek, A., Marek, O., 2013, Quay Cranes in Container Terminals. Transaction of Transport Sciences. Volume 6, 9-18.
2. Chao, Shih-Liang., and Lin, Yu., 2011, Evaluating advanced quay cranes in container terminals. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 47, Issue 4, 432-445.
3. Choi H., S, Won H., S, & Lee, C., 2013, Comparison of alternative ship-to-yard vehicles with the consideration of the batch process of quay cranes. *International Journal of Industrial Engineering*. 20(1-2), 84-98.
4. Choi, S., Im, H., and Lee, C., 2014, Development of an operating system for optimization of the container terminal by using tandem-lift quay crane. *Future Information Technology*, 399-404
5. Choo, Shawn, Diego Klabjan and David Simchi-Levi, 2010, Multiship Crane Sequencing with Yard Congestion Constraints, *Transportation Science*, Vol. 44, No. 1 (February), pp. 98-115
6. Delgado A., Jensen R.M., Janstrup K., Rose TH., Andersen K.H., 2012, A constraint programming model for fast optimal stowage of container vessel bays. *European Journal of Operational Research*, 220(1), 251-261.
7. Diabat, Theodorou, A, E., 2014, An integrated quay crane assignment and scheduling problem. *Computers & Industrial Engineering*, 73:115-123
8. Goodchild, A. V., 200, Crane double cycling in container ports: algorithms, evaluation, and planning, PhD dissertation, University of California, Berkeley.
9. Goodchild, A. V., & Daganzo, C. F., 2006, Double-cycling strategies for container ships and their effect on ship loading and unloading operations. *Transportation Science*, *40*(4), 473–483.
10. Goodchild, A. V., & Daganzo, C. F., 2007, Crane double cycling in container ports: Planning methods and evaluation. *Transportation Research Part B*, *41*(8), 875–891.
11. Hay, Cameron, 2016, Trends in multiple lifting, Spreader Container, World Port Development, *International Journal For Port Management*, June, https://www.ramspreaders.com/wp-content/uploads/2016/07/WPD-SingFlex-Tandem-40-Headblock-June-2016.pdf
12. Huang X., Shi F., Zhang H., 2012, SVM-Based Fuzzy Rules Acquisition System for Twin-Lift Spreader System, Chapter 9, 75-81. In: Wang X., Wang F., Zhong S. (eds) Electrical, Information Engineering and Mechatronics 2011. Lecture Notes in Electrical Engineering, vol 138. Springer, London. Retrieved from https://link-springer-com.sunymaritime.idm.oclc.org/chapter/10.1007%2F978-1-4471-2467-2_9
13. Hyongmo, J., 2015, The era of mega vessels and challenges to ports. *Pacific Economic Cooperation Council*, October, Retrieved from https://www.pecc.org/resources/infrastructure-1/2289-the-era-of-mega-vessels-and-challenges-to-port/file
14. Jiang Xinjia, , Ek Peng and Loo Hay Lee, 2015, Innovative Container Terminals to Improve Global Container Transport Chains, Chapter 1 in Lee Chung Yee and Qiang Meng, (2015) Handbook of Ocean Container Transport Logistics, Making Global Supply Chain Effective, *International Series in Operations Research & Management Science*, Springer.
15. Johansen Robert S., 2007, Twin-40 Container Operations … The Landside Part of the Equation, AAPA Facilities Engineering Seminar, JWD Group, A division of DMJM Harris, November, http://aapa.files.cms-plus.com/SeminarPresentations/07_FACENG_Johansen_Robert.pdf
16. Jordan, Michael, 2013, "Evolution of STS Cranes", World Port Development, May.
17. Kim, Kap Hwan and Hoon Lee, 2009, Trends and Future Challenges, Chapter 2, Container Terminal Operations: Current, http://www.springer.com/978-3-319-11890-1
18. Lashkari, S., Wu, Y., and Petering E.H., M., 2017, Sequencing duel spreader crane operations: Mathematical formulation and heuristic algorithm. *European Journal of Operational Research*. Edition 262, 521-534.

19. Lind, Derrick, Jonathan K. Hsieh and Michael A. Jordan, 2007, Tandem-40 Docking Container Crane and Their Impact on Terminals, Liftech, ASCE Ports 2007 Conference, San Diego, CA. http://www.liftech.net/wp-content/uploads/2013/03/Tandem-40-Dockside-Container-Cranes-and-Their-Impact-on-Terminals-Paper.pdf
20. Louppova Julia , 2016, A 6-at-a-time spreader to handle empties, Port Today, November 3. https://port.today/a-6-at-a-time-spreader-to-handle-empties/
21. MAREX, 2016, New System Promises Faster Handling for Empties. https://maritime-executive.com/article/new-system-promises-faster-handling-for-empties
22. OECD/ITF, 2015, The impact of Mega-ships, International Transportation Forum
23. Perina, O., & Barrons, A., 2015, Terminal Productivity: Optimizing the operational frontline. *Port Technology*, 66, August, Retrieved from https://www.porttechnology.org/technical_papers/terminal_productivity_optimizing_the_operational_front_line
24. Port of Rotterdam, (2015, APM Terminals Rotterdam the most productive terminal in Europe, September 14, Retrieved from https://www.portofrotterdam.com/en/news-and-press-releases/apm-terminals-rotterdam-the-most-productive-terminal-in-europe
25. Sea Trade Maritime News, 2018, Infrastructure costs need to be considered in building 24,000 teu boxships, http://www.seatrade-maritime.com/news/asia/infrastructure-costs-need-to-be-considered-in-building-24000-teu-boxships.html
26. Soderberg Erik, Michael Jordan and Simo Hoite, 2016, Concept High Productivity STS Cranes, Liftech Consulting Corp., *ASCE Copri Ports 2016 Conference*, New Orleans, Louisiana.
27. Song, J., n.d., Tandem operation and double cycling in container terminals. *Port Technology*: Edition 51. Retrieved from https://www.porttechnology.org/technical_papers/tandem_operation_and_double_cycling_in_container_terminals
28. Tierney, K., S. Voß, R. Stahlbock, 2013, A mathematical model of inter-terminal transportation. *Technical report*, IT University of Copenhagen, Rotterdam.
29. van, Marle, Gavin, 2015, Top 20 Ports: The productivity challenge, Container shipping trade, Lloyds Register, Sept. 04 http://www.containerst.com/news/view,top-20-ports-the-productivity-challenge_39089.htm
30. Wikipedia, 2017, List of largest container ships, https://wikivisually.com/wiki/List_of_largest_container_ships
31. World Cargo News, 2007, Container crane productivity and double cycling debate, July
32. Yahalom, Shmuel Z. and Changqian Guan, 2016, "Containership Port Time: The Bay Time Factor," *Maritime Economics & Logistics*, ISSN: 1388-1973, December, pp 1-17, online: September 12, 2016 (DOI: 10.1057/s41278-016-0044-6).
33. Yahalom, Shmuel Z. and Changqian Guan, 2017, "Containership Bay Time and Crane Productivity: Are They on the Path of Convergence?" *International Association of Maritime Economists, 2017,* Kyoto, Japan, June, 27-30.
34. Yi, Lin, Li Zhiyong, Tian Xiaofeng,(2016, Comparison and Selection of Twin 40 Quay Crane for Automated Terminal, Port & Waterway Engineering, No. 9, 519, September, https://www.ramspreaders.com0/wp-content/uploads/2016/10/TANDEM-LIFT-ARTICLE.pdf
35. Zhang, H. P., & Kim, K. H., 2009, Maximizing the number of dual-cycle operations of quay cranes in container terminals. *Computers & Industrial Engineering, 56*(3), 979–992.
36. ZPMC, n.d, Semi-automatic, http://www.nauticexpo.com/prod/zpmc/product-30643-416383.html
37. ZPMC, n.d., Spreaders. Retrieved from http://www.zpmcspreader.com/english

Brief Biography for the Presenter

[i] **Shmuel Yahalom** Ph.D. is a Distinguished Service Prof. of Economics and Transportation in the Dept. of Global Business and Transportation at the State Univ. of New York Maritime College, which he joined in 1978. He developed new evaluation methods for discharging containerships and containership routing standardization for efficient use of containership voyage time performance. His expertise are shipping, ports and terminal management, and supply chain.