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Comparing Cycle Times of Advanced Quay Cranes in Container Terminals

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ABSTRACT

The amount of international trade is rapidly increasing as a result of globalization. It is well known that as the size of a vessel becomes larger, the transportation cost per container decreases. That is, the economy-of-scale holds even in maritime container transportation. As a result, the sizes of containerships have been steadily increased for reducing transportation costs. In addition, various handling technologies and handling equipment have been introduced to increase the throughput capacities of container terminals. Quay crane (QC) that carries out load/unload operations plays the most important role among various handling equipment in terminals. Two typical examples of advanced QC concepts proposed so far are double trolley QC and supertainer QC. This paper suggests a method of estimating the expected value and the standard deviation of the container handling cycle time of the advanced QCs that involve several handling components which move at the same time. Numerical results obtained by the proposed estimation procedure are compared with those obtained by simulation studies. In order to demonstrate the advantage of advanced QCs, we compared their expected cycle times with those of a conventional QC.

Keywords: Cycle Time, Advanced Quay Crane, Container Terminal, Statistics

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1. INTRODUCTION

Over 90% of the world cargoes were shipped by vessels and the majority of them were moved through the container transportation. The container traffic forecast report for the year 2007 in a United Nations showed that the annual growth rate for global container trade volumes from 2005 to 2015 was estimated to be 7.6% (Yang, 2012). Therefore, the container transportation is very important for the world cargo logistics, which makes a container terminal play an essential role in the transportation network. All ports wish to increase the efficiency of handling operations so more vessels decide to call at the port.

The container handling process involves the loading/unloading activities of containers on/from ships, the transportation of containers between the berth and the yard, and the storage operation in terminals. The performance of the entire terminal depends on the synchronization among the handling equipment and the productivity of each piece of equipment.

The quay cranes (QCs), which perform unloading operations from and loading operations onto the vessels, play the most important role among handling equipment in terminals. Some advanced QCs have been developed to increase the number of lifts per unit time (twin-lift QC or tandem lift QC) or the number of containers per lift (double trolley QC [DQC] or supertainer QC [SQC]). Twin-lift QCs and tandem lift QCs attempt to increase the number of containers per lift. This paper does not consider new QCs with more containers per lift, because the cycle time per lift of those QCs is similar to the traditional single trolley QC, but considers new conceptual QCs with increased number of lifts per unit time resulting from decomposing the cycle time into multiple segments. DQC or SQC attempts to increase the number of lifts per unit time by shortening the cycle time for a lift. In the operation of DQC or SQC, the process of moving a container between a vessel and a truck in the apron is decomposed into multiple segments, each of which is assigned to different component of the QC for reducing the entire cycle time. These QCs are studied in this paper.

The cycle time in this paper indicates the system cycle time which represents the interval time between consecutive loading or discharging by a QC considering all the interference time between different components of the QC. The concept of the cycle time is similar with the takt time in manufacturing systems. “Takt time” is the amount of time that must elapse between two consecutive unit completions in order to meet the demand (Wikipedia). This concept of the cycle time is different with the mechanical cycle time of each component of a QC, which considers only the mechanical speed and the movement distance of such a component as the trolley, the elevator, the buffer, and the hoist. Note that this mechanical cycle time does not consider the interference time between different components of a QC. Note also that the cycle time depends not only on the mechanical cycle time of each component but also on the starting and ending positions for the movement of containers (Kim *et al.,* 2012). That is, in the land side, more than one parking positions are provided for trucks, while, in the vessel side, a container may be picked up from various slots, which are located at various tiers and rows in a ship bay (Figure 1). Therefore, the cycle time of a QC cannot be evaluated just by using the constant mechanical cycle times of components but needs to be evaluated by a statistical analysis. Because loading and unloading operations are not mixed in a consecutive operation sequence for a QC, this study only considers the single command cycle operation of a QC. The simulation study may be used for the evaluation of the cycle time. However, considering that the long time is necessary for the development of the simulation program, the statistical analysis may be a good alternative for obtaining the estimate of the cycle time in a short time.

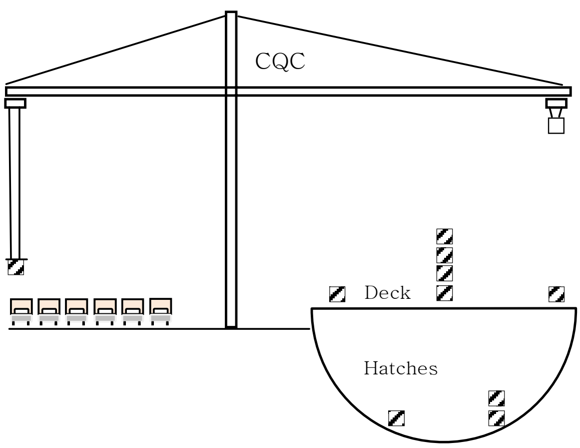

Figure 1. Illustration of various positions of containers (Kim *et al.,* 2012).

This paper is organized as follows: Section 2 introduces the background of this study. Section 3 presents the operation of two kinds of advanced QC and the statistical models for estimating the expected values and the variances of cycle times. Section 4 validates the models by using simulation; some numerical experiments are carried out to estimate the improvement of new QCs over the traditional QC. Section 5 provides conclusions.

2. BACKGROUND

There have been many studies on QC scheduling problems. Daganzo (1989) studied QC scheduling problems for multiple container vessels. Peterkofsky and Daganzo (1990) developed a branch and bound solution method for solving the QC scheduling problem. However, they did not consider the interference between QCs. Lim *et al.* (2004) used dynamic programming algorithms, a probabilistic tabu search, and a squeaky wheel optimization heuristic to solve the QC scheduling problem for multiple container vessels by taking into account non-interference constraints. Kim and Park (2004) also discussed that problem with non-interference constraints for one vessel. They tried to minimize the weighted sum of the makespan of the container vessel and the total completion time of all QCs by using branch and bound method and a heuristic algorithm called ‘greedy randomized adaptive search procedure (GRASP).’ Jung *et al.* (2006) proposes a heuristic search algorithm GRASP for constructing a schedule of QCs in a way of minimizing the makespan and considering interference among yard cranes. Lim *et al.* (2007) studied an *m*-parallel machine scheduling problem with a non-crossing constraint motivated by crane scheduling in ports and allocation time for QC. A simulated annealing heuristic that uses random neighborhood generation is provided in that paper to find solution and large experiment. Meisel and Bierwirth (2011) recognized that there is no platform available to compare the solutions and investigating conditions of previous researches in the QC scheduling problem. Therefore, they suggested a unified approach for evaluating the performance of different model classes and solution procedures. These researches proposed a QC scheduling method for a given cycle time of QC operation. However, the cycle time may vary so much depending on the type of QC. Recently, there have been a few studies on the advanced QC in container terminals. Chao and Lin (2011) evaluated the performance of some advanced QCs in a container terminal. In their paper, they describe four types of QC: conventional QC (CQC), QC with twin-lift spreader, DQC, and double-sided operation QC system. Spreader is a component of QC. It has a locking mechanism at each corner that attaches the four corners of a container. Multi-lift spreaders can lift more than one container at a time. Double-sided operation QC system uses many CQCs. “By constructing an indented berth or using a jumbo

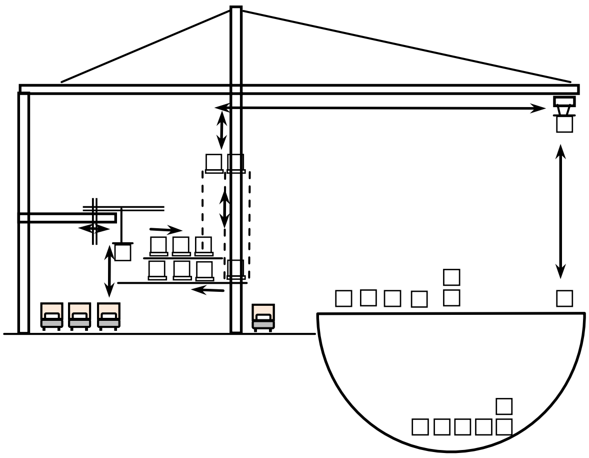

Figure 2. Quay crane with elevators (Kim *et al.*, 2012).

floating platform that can carry several QCs, the additional QCs could service a ship from both sides" (Chao and Lin, 2011). A two-phase method was developed to select a suitable QC based on a survey of the terminal operators in Kaohsiung port. The paper evaluated various types of QC for some selected factors by a survey.

Lee *et al.* (2005) calculated the cycle time of dual cycle elevator conveyor QC based on the design parameters and compared it with the ones of CQC. Figure 2 (Kim *et al.*, 2012) shows a conceptual design of the QC in which two elevators are installed between the quayside trolley and the landside trolley. These elevators are responsible to the vertical movement of containers. There are two dedicated conveyors: one is used to move outbound containers while the other moves inbound containers. Based on the analysis of this QC, it was expected to increase the loading capacity from 38 boxes/hour, which is the productivity of traditional QC, to 94 boxes/hour. To estimate the loading capability of a QC, they used not only the velocity and the acceleration of the driving equipment for the ship trolley but also the moving distance of each component of the QC.

However, previous papers have not considered the waiting time for a trolley to wait for the arrival of a container delivered by the other trolley or elevator. This study suggests a method to estimate its cycle time that considers the uncertainty in the movement distance of trolleys and the possible waiting time for the handover of a container between adjacent pieces of handling equipment.

3. MODELING CYCLE TIME OF QUAY CRANE OPERATION

3.1 Operation of Advanced QC

During the traditional loading operation, the spreader of a CQC picks up a loading container from a truck, hoists it up, and moves it in the horizontal direction. After the horizontal movement, the spreader moves down and releases the container onto a ship bay. For discharging a container, the procedure is performed in the reverse order.

The time for a QC to transfer a container from a truck to a vessel, and vice versa, depends not only on the speed of the trolley but also on the position of the container at the starting point and the ending point of the transfer (Figure 1). This paper assumes that the transfer time is a random variable following Normal distribution $N(\mu, \sigma^2)$.

In this paper, two kinds of advanced QC are analyzed to compare the cycle time of those QCs with that of the traditional QC. The two new types of QC are DQC and SQC. The DQC is designed to deploy two trolleys to a QC. There is a small platform in the middle of the QC body for transferring containers between the quay-side trolley and the land-side trolley (Figure 3). SQC deploys two trolleys and one traverser to perform container movements (Figure 4). The platform or traverser can hold one or more than one container.

In the DQC, after a container is transferred onto the platform by the quay-side trolley, the empty quay-side trolley returns back to a ship bay. The container on the platform is unloaded to a transporter by the land-side trolley. Thus, a cycle is divided into two segments.

In the SQC, firstly, (1) a container is transferred to the traverser by the quay-side trolley, and the empty trolley returns back to a ship bay. Secondly, (2) the traverser moves it horizontally to transfer it to the land-side trolley. Finally, (3) the container is unloaded to a transporter by the land-side trolley. Thus, the cycle is divided into three segments. The next subsection provides a mathematical model for estimating the productivity of advanced QC considering the physical speed of each trolley, traverser, and the buffer conveyor on the platform.

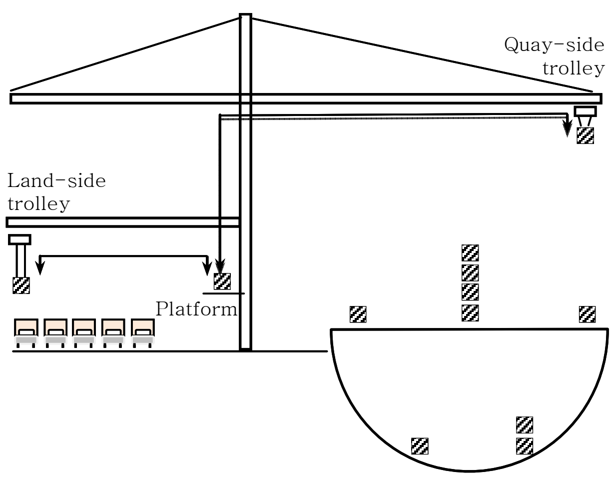

Figure 3. Operation of the double trolley quay crane (Kim *et al.,* 2012).

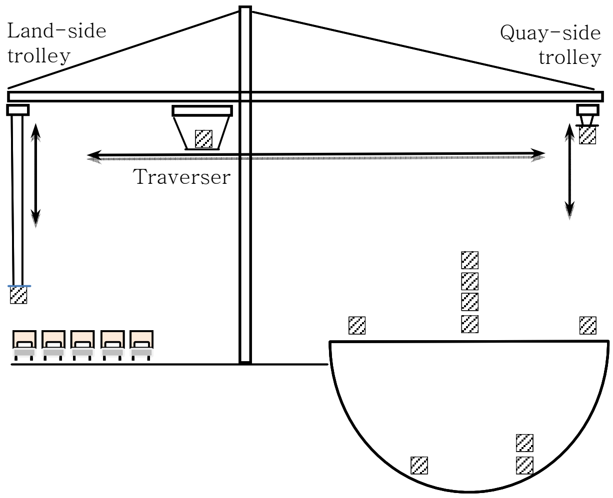

Figure 4. Operation of the supertainer quay crane (Kim *et al.*, 2012).

3.2 Modeling Cycle Time of QC

Let the time for an elementary movement of a CQC be a random variable following Normal distribution $N(\mu, \sigma^2)$. To estimate the expected value and the variance of the cycle time of two advanced QCs, the probability density function (PDF) of the operation time of each trolley and the traverser or the buffer conveyor must be estimated. The operation time of a trolley or the traverser depends on the physical design and the position of the container that the QC has to transfer. We call the cycle time calculated from the physical speed and the distance as "technical cycle time."

However, when these multiple trolleys or the traverser work together, there are interferences among those handling components and the cycle time may be longer. It means that the operation of advanced QC resembles the multi-stage material handling system (Vidovic and Kim, 2006). The technical cycle time of each stage affects not only the cycle time of the equipment at that stage but also the waiting time of neighboring equipment. And this waiting time is mutually dependent on the physical cycle times of neighboring equipment. To estimate the cycle time of multi-stage system of advanced QC, a statistical model is derived by using the PDF of the processing time of each component.

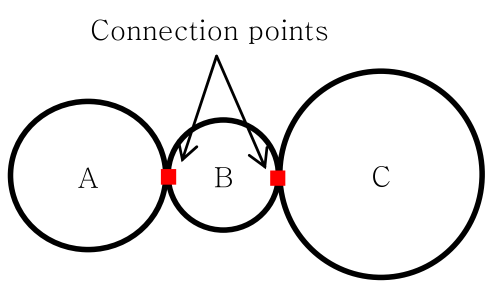

Figure 5. The three-stage handling system.

Consider the model for the most complex system, corresponding to SQC, which involves three stages of handling the transfer of a container. Each piece of handling component has a technical cycle time that can be estimated from its physical specification. This part analyses the cycle time of the entire system consisting of three stages.

Suppose that three components (A, B, and C) of a QC work independently and they have their own technical cycle times X_1, X_2, and X_3 (Figure 5), which are independent random variables. Let:

X_1: technical cycle time of component A, $X_1 \sim N(\mu_1, \sigma_1^2)$,
X_2: technical cycle time of component B, $X_2 \sim N(\mu_2, \sigma_2^2)$,
X_3: technical cycle time of component C, $X_3 \sim N(\mu_3, \sigma_3^2)$.

Because the two components A and B must meet each other for transferring a container, the combined cycle time of components A and B can be expressed by $X_1^{'}=X_2^{'} = \text{Max}\{X_1, X_2\}$. We assume that an artificial component has the combined cycle time $X_2^{'}$. If the artificial component is combined again with component C, then the new combined cycle time can be obtained by $X_3^{'}=X_2^{''}= \text{Max}\{X_2^{'}, X_3\}$. The cycle time $X_2^{''}$ is the combined cycle time of three components in the system. It involves the waiting times of components in two handover points. Thus, it is the combined with the cycle time of the entire system.

Both the models for DQC and SQC may be represented by the three-stage model. However, in the model for DQC, we assume that the second component, B, is a platform with technical cycle time $X_2 = 0$.

The basic procedure to find the final combined cycle time of the system consists of two steps. In each step, the PDF of the maximum of two random variables with normal distributions needs to be derived. Therefore, the next section introduces a statistical model for deriving the PDF.

3.3 Maximum of Two Independent Gaussian Random Variables

Let $X = \text{Max}(X_1, X_2)$, where X_1 and X_2 are Gaussian random variables following distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, respectively. Let ρ be the correlation coefficient of (X_1, X_2). Then, X has the probability density function $f(x) = f_1(x)+f_2(x)$ $-\infty < x < \infty$ (Cain, 1994), where

$$f_1(x)=\frac{1}{\sigma_1}\phi\left(\frac{\mu_1-x}{\sigma_1}\right)\Phi\left(\frac{-\left(\frac{\mu_2-x}{\sigma_2}\right)+\rho\left(\frac{\mu_1-x}{\sigma_1}\right)}{\sqrt{1-\rho^2}}\right)$$

and $$f_2(x)=\frac{1}{\sigma_2}\phi\left(\frac{\mu_2-x}{\sigma_2}\right)\Phi\left(\frac{-\left(\frac{\mu_1-x}{\sigma_1}\right)+\rho\left(\frac{\mu_2-x}{\sigma_2}\right)}{\sqrt{1-\rho^2}}\right) \quad (1)$$

and φ(·) and Φ(·) are, respectively, the PDF and the cumulative distribution function of the standard normal distribution.

Because the technical cycle times of these components in an advanced QC are independent, the correlation coefficient of two distributions $\rho = 0$. We have the moment-generating function of Eq. (1) below.

$$\mu_r' = E(X^r) = \int_{-\infty}^{\infty} x^r f_1(x)dx + \int_{-\infty}^{\infty} x^r f_2(x)dx$$

$$m(t) = \exp\left[t\mu_1 + \frac{1}{2}t^2\sigma_1^2\right]\Phi\left(\frac{\mu_1 - \mu_2 - t\sigma_1^2}{\theta}\right) + \exp\left[t\mu_2 + \frac{1}{2}t^2\sigma_2^2\right]\Phi\left(\frac{\mu_2 - \mu_1 - t\sigma_2^2}{\theta}\right)$$

where $\theta = \left(\sigma_1^2 + \sigma_2^2\right)^{\frac{1}{2}}$

The r-th moment ($r \geq 1$) of X is

$$\mu_r' = E(X^r) = \int_{-\infty}^{\infty} x^r f_1(x)dx + \int_{-\infty}^{\infty} x^r f_2(x)dx \qquad (2)$$

where f_1 and f_2 are given by (1). The integrals in (2) are quite difficult to evaluate directly, and hence μ_r', for a given r, is more easily obtained either by expanding the moment-generating function or, equivalently, as $\mu_r' = E(X^r) = m^r(0)$, where $m^r(t) d^r m(t)/dt^r$.

Differentiating $m_r(t)$ twice with respect to t and setting $t = 0$ yields

$$m_1'(0) = \mu_1\Phi\left(\frac{\mu_1 - \mu_2}{\theta}\right) + \left(\frac{\sigma_1^2}{\theta}\right)\phi\left(\frac{\mu_2 - \mu_1}{\theta}\right)$$

and

$$m_1'' = \sigma_1^2\Phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) + \frac{\mu_1\sigma_1^2}{\theta}\phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) + \frac{(\mu_2 - \mu_1)\sigma_1^4}{\theta^3}\phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) + \mu_1 m_1'(0)$$

If the symmetry between $m_1(t)$ and $m_2(t)$ is noted, $m_2'(0)$ and $m_2''(0)$ may be obtained by interchanging (μ_1, σ_1) and (μ_2, σ_2) in the expressions for $m_1'(0)$ and $m_1''(0)$, respectively. It follows that the mean and the second moment of X is:

$$E(X) = m_1'(0) + m_2'(0)$$
$$= \mu_1\Phi\left(\frac{\mu_1 - \mu_2}{\theta}\right) + \mu_2\Phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) + \left(\frac{\sigma_1^2 + \sigma_2^2}{\theta}\right)\phi\left(\frac{\mu_1 - \mu_2}{\theta}\right) \qquad (3)$$

$$E(X^2) = m_1''(0) + m_2''(0)$$
$$= \left(\mu_1^2 + \sigma_1^2\right)\Phi\left(\frac{\mu_1 - \mu_2}{\theta}\right) + \left(\mu_2^2 + \sigma_2^2\right)\Phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) - (\mu_1 + \mu_2)\theta\phi\left(\frac{\mu_2 - \mu_1}{\theta}\right) \qquad (4)$$

while $Var[X] = E[X^2] - (E[X])^2 \qquad (5)$

Therefore, from the first two moments of X, the distribution of the maximum of bivariate normal random variables is given with values of mean and variance.

For example, if X_1 and X_2 are Gaussian random variables with distributions $X_1 \sim N(50, 15^2)$ and $X_2 \sim N(70, 25^2)$, the maximum of two independent Gaussian random variables $X = \text{Max}(X_1, X_2)$ and $X \sim N(74, 21^2)$ (Phan and Kim, 2012).

4. EVALUATION OF THE STATISTICAL MODEL BY SIMULATION

The cycle times of container handling from the statistical model are compared with the results from a simulation model. The simulation model is developed for SQC and DQC by using eM-Plant software. In the simulation model, the technical cycle times of these components are generated randomly using normal distributions. The simulation model runs during 12 working hours.

4.1 The Cycle Time of CQC

Numerical examples were generated based on data collected from a real system. The elementary movements by CQC were observed: picking up a container, moving with container, moving without container, and releasing container. Time for each operation is recorded in seconds. The Jarque-Bera (JB) test was done for the null hypothesis which tests whether times for elementary movements are normally distributed or not (Table 1). The results of this test are compared with the critical value at 5% level for 2 degrees of freedom in Table 1. The JB value < χ^2_{critical} (= 5.99) means that the times of all the elementary movements follow normal distributions.

Let:

X_P be the picking up time, and $X_P \sim N(19.34, 9.77^2)$,

X_M be the moving time of trolley, and $X_M \sim N(97.55, 38.37^2)$, which is the sum of the empty and the laden moving time of the trolley,

X_R be the releasing time, and $X_R \sim N(29.63, 11.16^2)$.

Let X is the technical cycle time of CQC, then $X = X_P + X_M + X_R$, $X \sim N(146.52, 41.134^2)$.

Table 1. Result of Jarque-Bera (JB) test for normal distributions

Elementary movement of QC	Skewness	Kurtosis	JB
Empty movement of trolley	0.572	1.546	*3.138*
Picking up	0.791	1.664	*3.929*
Laden movement of trolley	0.609	1.238	*4.204*
Releasing	0.529	1.618	*2.777*
Mechanical cycle time	0.426	1.010	*4.296*

The technical moving time of the trolley of CQC depends on the distance between the starting and the ending points of the trolley movement and the speed of the trolley. Therefore, the moving time of trolley, X_M, may be changed when the specification of a QC changes.

For the experiment, the mean and the standard deviation of X_M were generated from uniform distributions. The mean values were obtained from uniform distribution of U(70, 130). The standard deviations were acquired by dividing the mean values by a uniformly distributed random number between 2 and 4. Thus, the coefficient of variation, σ/μ, was between 0.25 and 0.5.

4.2 The Cycle Time of DQC

To generate the technical cycle time of components in advanced QC, data collected from the CQC were used. The time for picking up or releasing a container for the DQC and SQC was set to be the same as those for CQC. It was assumed that the mean value of the total moving time for a container from a ship bay to a transporter in advanced QC is equal to that for CQC.

The moving time X_M in CQC is a random variable following normal distribution $N(\mu, \sigma^2)$, and it includes the time for horizontal and vertical movements. $X_P = N(\mu_P, \sigma_P^2)$ and $X_R = N(\mu_R, \sigma_R^2)$ are the time for picking up and releasing a container by the spreader.

The cycle time of components A and B in DCQ are assumed to follow $N_1(\mu_1, \sigma_1^2)$ and $N_2(\mu_2, \sigma_2^2)$. In loading operation, component A (the quay-side trolley) picks up a container from the vessel, moves up and travels in the horizontal direction until it reaches the platform. And then, it moves down and releases the container onto the platform and comes back to the vessel side. Component B (the land-side trolley) moves down to pick up container from the platform, moves up and travels in the horizontal direction until it reaches the parking position of trucks in the land side. And then, it moves down to release the container onto a transporter and comes back to the position of the platform. When applying the statistical model, it was assumed that there are three components including the platform in the second stage, which has the processing time of zero. The processing times for these two trolleys are:

$$\begin{aligned} &\mu_1 = \mu_P + a\mu + t_l + t_r + t_l && \sigma_1^2 = \sigma_P^2 + a^2\sigma^2 \\ &\mu_2 = t_l + \mu_P + t_l + b\mu + \mu_R && \sigma_2^2 = \sigma_P^2 + b^2\sigma^2 + \sigma_R^2 \\ &a + b = 1 \end{aligned} \tag{6}$$

where t_l is the time for the trolley to move a container down to the platform or move up. It depends on the speed of the trolley and the distance of the vertical movement. It is assumed to be 2 seconds (the speed of the trolley is 4 m/s and the distance is 8 m). The time for releasing a container on the platform, t_r, is assumed to be a constant (around 10 seconds) because the releasing is a simple operation. To generate the cycle time value of each component, the value of a was obtained from a uniform distribution U(0.6, 0.7).

4.3 The Cycle Time of SQC

Let the cycle time of components A, B, and C in SCQ follows $N_1(\mu_1, \sigma_1^2)$, $N_2(\mu_2, \sigma_2^2)$, and $N_3(\mu_3, \sigma_3^2)$, respectively. During the loading operation, component A (quay-side trolley) will pick up a container from the vessel and move it in the horizontal direction to reach component B (the traverser). Then, it releases the container down onto the traverser and comes back to the vessel. Component B moves the container to the land-side trolley (component C) in the horizontal direction. After component C arrives at the position of the traverser, it picks up the container from the traverser. Then, the empty traverser (component B) comes back the ship side (near to the quay side trolley). Then, component C moves down and releases the container onto a transporter and moves up to pick up the next container from component B. The cycle times for these three components are:

$$\begin{aligned} &\mu_1 = \mu_P + a\mu + t_l + t_r + t_l && \sigma_1^2 = \sigma_P^2 + a^2\sigma^2 \\ &\mu_2 = b\mu && \sigma_2^2 = b^2\sigma^2 \\ &\mu_3 = t_l + \mu_P + t_l + c\mu + \mu_R && \sigma_3^2 = \sigma_P^2 + c^2\sigma^2 + \sigma_R^2 \\ &a + b + c = 1 \end{aligned} \tag{7}$$

In above equations, processing times for the spreader to reach the traverser t_l, to pick a container μ_P, and to release a container t_r on the traverser or a transporter are assumed the same as in Section 4.2. To generate the cycle time value of each component, the value of a and b were obtained from the uniform distribution U(0.25, 0.4) and U(0.2, 0.35), respectively.

4.4 Evaluation of Accuracies of Statistical Estimators by a Simulation

Tables 2 and 3 show the input parameters mean and the standard deviation of CQC's cycle time. From these input parameters, the mean and the standard deviation of the technical cycle time for each component of DQC, (X_1, X_2) were generated by using Eq. (6). The technical cycle time for each component of SQC, (X_1, X_2, X_3) were made by using Eq. (7).

The expected value and the standard deviation of the cycle times of DQC or SQC were estimated from the statistical models, Eqs. (3), (4), and (5), and they were compared with those values obtained from the simulation. When the realistic values of technical cycle times of the components were used, the results showed that the application of the statistical model introduced an average error in the expected cycle time of 7.7%. The average error in the standard deviation was around -9.5%. For the case of SQC, the error was 1.6% and -9.9% for the expected value and the standard deviation of the cycle time, respectively, which are smaller than in the case of DQC.

Table 2. Evaluation of the statistical estimator for the cycle time of double trolley quay crane (DQC) by using simulation

	CQC		DQC X_1		DQC X_2		**DQC statistical model (A)**		***DQC simulation model (B)***		**Error [(A)-(B)] / (A)**		**Mean DQC/ mean CQC**
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
1	124	29	79.2	18.5	79.8	17.3	**89.6**	**14.8**	***82.6***	***16.5***	0.08	-0.12	0.72
2	146	45	92.0	28.1	89.5	21.7	**105.0**	**21.0**	***95.6***	***20.9***	0.09	0.00	0.72
3	178	55	111.5	34.0	102.1	24.9	**124.0**	**25.7**	***113.9***	***24.9***	0.08	0.03	0.70
4	170	50	108.9	32.0	97.0	22.8	**119.3**	**24.4**	***110.1***	***23.8***	0.08	0.03	0.70
5	161	55	100.3	34.2	96.0	25.2	**115.2**	**25.3**	***104.6***	***24.6***	0.09	0.03	0.72
6	136	39	85.0	24.3	86.0	20.2	**98.1**	**18.4**	***89.9***	***19.3***	0.08	-0.05	0.72
7	177	57	117.6	38.4	94.3	23.2	**126.2**	**30.3**	***118.4***	***29.3***	0.06	0.03	0.71
8	171	36	113.0	24.2	93.2	18.4	**117.7**	**20.2**	***113.0***	***23.7***	0.04	-0.18	0.69
9	146	51	98.8	35.0	82.6	20.9	**108.3**	**26.7**	***99.6***	***25.1***	0.08	0.06	0.74
10	123	31	79.8	20.4	78.8	17.7	**90.1**	**15.8**	***82.6***	***16.8***	0.08	-0.06	0.73
11	151	47	97.3	30.2	89.3	21.6	**108.4**	**22.6**	***99.1***	***28.2***	0.09	-0.25	0.72
12	129	34	81.3	21.4	82.9	18.7	**93.5**	**16.5**	***85.8***	***17.8***	0.08	-0.08	0.73
13	167	53	111.3	35.8	91.5	22.2	**120.0**	**27.9**	***112.1***	***34.4***	0.07	-0.23	0.72
14	129	25	84.5	16.8	79.6	16.4	**91.6**	**13.8**	***85.0***	***16.3***	0.07	-0.18	0.71
15	169	62	110.0	40.5	94.1	25.3	**122.2**	**30.5**	***112.9***	***38.4***	0.08	-0.26	0.72
16	154	52	101.3	34.4	88.5	22.4	**112.1**	**25.9**	***102.4***	***24.6***	0.09	0.05	0.73
17	143	44	94.4	29.7	84.2	20.3	**104.2**	**22.4**	***95.6***	***21.4***	0.08	0.04	0.73
18	129	39	79.8	23.9	84.7	20.6	**95.0**	**18.3**	***87.3***	***19.8***	0.08	-0.08	0.74
19	147	51	90.6	31.0	91.3	24.2	**106.6**	**22.9**	***96.8***	***23.3***	0.09	-0.02	0.73
20	145	44	96.2	29.7	84.3	20.1	**105.3**	**22.6**	***96.9***	***21.8***	0.08	0.04	0.73
21	134	44	89.6	30.0	79.7	19.8	**99.5**	**22.5**	***90.9***	***28.2***	0.09	-0.26	0.74
22	178	44	121.7	30.3	92.0	19.3	**125.8**	**25.8**	***122.0***	***26.1***	0.03	-0.01	0.71
23	147	50	90.8	30.4	91.4	23.8	**106.5**	**22.5**	***96.8***	***22.9***	0.09	-0.02	0.73
24	140	30	85.9	18.2	89.2	18.0	**97.9**	**15.0**	***91.1***	***17.4***	0.07	-0.16	0.70
25	151	38	97.9	25.1	88.2	19.2	**106.2**	**19.5**	***98.3***	***24.2***	0.07	-0.24	0.70
26	157	56	103.0	37.1	89.2	23.4	**114.5**	**27.8**	***105.2***	***34.9***	0.08	-0.26	0.73
27	155	45	97.0	28.3	92.9	21.9	**109.3**	**21.3**	***99.7***	***26.1***	0.09	-0.23	0.71
28	152	31	100.2	20.8	86.9	17.4	**105.6**	**17.0**	***99.9***	***20.4***	0.05	-0.20	0.70
29	141	34	89.1	21.8	87.4	18.8	**99.8**	**16.9**	***91.7***	***17.9***	0.08	-0.06	0.71
30	127	38	85.7	26.5	77.1	18.4	**94.7**	**20.0**	***86.8***	***25.1***	0.08	-0.25	0.74
Average											7.7%	-9.5%	**71.8%**

CQC: conventional quay crane, SD: standard deviation.

On the average, the cycle time of the advanced QC was shorter than that of CQC. The expected cycle time of SQC was only 63.7% of that of CQC. The expected cycle time of DQC was around 72% of that of CQC according to the result from the statistical models.

5. CONCLUSIONS

This study showed that a statistical model may be successfully applied to estimate the cycle times of advanced QC's handling operation. We found that the results of the estimation are accurate according to the evaluation by a simulation study. It was also found that the productivity of DQC and SQC was approximately 140%–160% of CQC.

The statistical model introduced in this paper can be used for finding the optimal design of the traverse or the platform for DQC or SQC in future researches. In addition, the detailed analysis of the horizontal and vertical movement based on the positions of containers on a vessel and the positions of transporters may improve the accuracies of the estimators proposed in this study.

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Table 3. Evaluation of the statistical estimator for the cycle time of supertainer quay crane (SQC) by using simulation

	CQC		SQC						**SQC statistical model (A)**		***SQC simulation model (B)***		**Error [(A)-(B)] / (A)**		**Mean SQC/ mean CQC**
			X_1		X_2		X3								
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
1	155	41	67.1	15.5	27.5	9.8	97.3	18.6	**98.5**	**17.2**	***96.4***	***19.0***	0.02	-0.11	0.64
2	122	34	57.5	13.9	14.6	6.0	87.3	17.2	**88.2**	**16.1**	***86.9***	***17.3***	0.01	-0.07	0.72
3	163	40	71.0	15.6	36.5	11.8	92.9	16.2	**94.8**	**14.5**	***92.1***	***16.5***	0.03	-0.14	0.58
4	175	48	69.9	16.5	37.8	13.7	104.7	21.2	**105.9**	**19.6**	***103.8***	***21.5***	0.02	-0.09	0.60
5	128	41	62.7	17.1	23.8	11.4	79.1	15.9	**82.4**	**14.0**	***80.3***	***15.8***	0.03	-0.13	0.64
6	148	46	70.2	18.9	19.9	8.8	95.8	21.2	**98.6**	**18.8**	***97.5***	***21.1***	0.01	-0.13	0.66
7	144	31	64.6	13.2	23.7	6.7	92.7	14.9	**93.4**	**14.1**	***93.9***	***14.9***	0.00	-0.06	0.65
8	122	33	53.9	12.9	18.4	7.5	87.5	17.1	**88.0**	**16.3**	***87.0***	***17.2***	0.01	-0.05	0.72
9	173	37	79.3	16.0	37.2	10.3	93.9	15.0	**97.2**	**13.1**	***95.2***	***14.9***	0.02	-0.13	0.56
10	167	53	75.9	20.6	34.3	14.6	94.3	20.2	**98.9**	**17.4**	***94.8***	***19.9***	0.04	-0.15	0.59
11	160	40	66.7	14.9	32.2	10.8	98.5	18.2	**99.4**	**17.0**	***97.6***	***18.6***	0.02	-0.09	0.62
12	121	24	59.9	12.0	20.1	5.2	78.1	11.8	**79.3**	**10.8**	***78.9***	***11.7***	0.00	-0.09	0.66
13	145	39	67.9	16.2	23.0	8.6	91.3	17.4	**93.3**	**15.6**	***90.5***	***17.6***	0.03	-0.13	0.64
14	165	38	72.9	15.3	40.7	12.1	89.1	14.5	**91.7**	**12.7**	***90.2***	***14.4***	0.02	-0.13	0.55
15	173	43	69.4	15.4	39.8	13.1	101.5	18.7	**102.5**	**17.4**	***100.7***	***19.1***	0.02	-0.09	0.59
16	173	45	76.9	17.7	42.3	14.4	91.5	16.4	**95.5**	**14.2**	***91.2***	***16.3***	0.05	-0.15	0.55
17	125	30	52.3	11.8	19.0	6.6	90.9	16.4	**91.1**	**16.0**	***90.1***	***16.8***	0.01	-0.05	0.73
18	126	29	62.5	13.6	25.3	8.2	75.2	12.1	**77.8**	**10.8**	***74.5***	***12.4***	0.04	-0.15	0.62
19	142	33	63.1	13.6	18.6	5.9	97.7	17.2	**98.2**	**16.5**	***96.8***	***17.6***	0.01	-0.07	0.69
20	132	41	57.5	14.9	29.1	13.5	82.9	17.0	**84.4**	**15.5**	***84.2***	***16.9***	0.00	-0.09	0.64
21	128	31	54.7	12.3	16.6	5.8	94.1	17.3	**94.3**	**16.9**	***93.2***	***17.7***	0.01	-0.05	0.74
22	165	38	66.9	14.1	32.4	9.9	102.7	18.0	**103.3**	**17.2**	***104.3***	***18.0***	-0.01	-0.05	0.63
23	150	44	65.8	16.5	31.4	12.9	90.5	18.3	**92.5**	**16.4**	***90.1***	***18.3***	0.03	-0.12	0.62
24	156	49	69.6	18.6	21.3	9.3	102.1	23.5	**104.2**	**21.2**	***104.1***	***23.4***	0.00	-0.10	0.67
25	174	53	67.1	16.9	40.0	16.4	104.2	23.2	**105.5**	**21.4**	***103.8***	***23.2***	0.02	-0.08	0.61
26	142	30	60.4	12.3	28.0	7.7	91.3	14.3	**91.7**	**13.8**	***92.4***	***14.3***	-0.01	-0.04	0.64
27	149	45	64.3	16.3	21.0	8.8	100.9	22.4	**102.1**	**20.9**	***100.8***	***22.6***	0.01	-0.09	0.69
28	155	32	68.4	13.4	21.2	5.6	102.8	16.3	**103.3**	**15.7**	***104.1***	***16.3***	-0.01	-0.04	0.67
29	171	35	79.5	15.4	28.0	7.2	100.4	15.7	**102.4**	**14.1**	***101.7***	***15.7***	0.01	-0.11	0.60
30	177	43	84.4	19.0	28.1	9.0	101.5	18.3	**105.6**	**16.0**	***100.7***	***18.7***	0.05	-0.17	0.60
Average													0.02	-9.9%	**63.7%**

CQC: conventional quay crane, SD: standard deviation.

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