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Evaluation Models for the Container Handling Times of the Automated Transfer Crane in Container Terminals

Ki Young Kim†

Department of International Logistics, Division of International Relations, Dongseo University

컨테이너 터미널에서 자동화된 트랜스퍼 크레인의 컨테이너 취급시간을 위한 평가모형

김기영

동서대학교 국제관계학부 물류유통학전공

The container handling times of automated transfer cranes(ATCs) significantly affect the productivity of container terminals. In this paper, evaluation models for the container handling times of ATCs are suggested for import container blocks with different transfer point configurations. Firstly, evaluation models for various motion times of stacking and retrieving operations of ATC are suggested for two basic alternatives of import container blocks. In addition, in considering the space allocation, evaluation methods for the container handling times of ATC are suggested. Finally, the container handling times for each case are compared with each other in order to analyze how the block shape and the transfer point locations affect the container handling times of ATC.

Keyword: Container terminal, Material handling, Space allocation, Storage

1. Introduction

The container handling times of the handling equipment significantly affect the productivity of container terminals. Recently, as a way of increasing storage capacity on the same ground slot in the yard, more rubber tyred gantry(RTG) and rail mounted gantry(RMG) are popularly used than straddle carriers. If RTG and RMG are automatic or semi-automatic, they are called automated transfer cranes(ATCs) in this paper.

The productivity of ACTs is affected by their capacities(their speeds), the shape of container block and the locations of transfer points. In this paper, evaluation models to estimate the container handling times of ATC for the two basic alternatives of import container blocks are suggested as a function of the container block shape and the transfer point configuration. Also, evaluation models to estimate the container handling times of ATCs are suggested in considering the space allocation. Using the models suggested in this paper, we can analyze how the block shape and the transfer point locations affect the container handling times of ATC.

There have been many research papers related to

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†Corresponding author : Professor Ki Young Kim, San 69-1, Churye-2dong, Sasang-ku, Busan, 617-716, South Korea, Tel : 82-51-320-1637, Fax : 82-51-320-1630; E-mail : kiykim@gdsu.dongseo.ac.kr
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container terminals. Among them, the research related to yard operations in container terminals is as follows;

Martin(1981) suggested a heuristic procedure for a containership load planning in a transfer crane based on a container terminal. Lee(1987) studied on improving the productivity of Busan container terminal system, focusing on its subsystem such as a ship operation system, a storage system and a transfer system. Kim(1998) provided various optimal and heuristic methods for routing straddle carriers and transfer cranes during the loading of export containers. Chen(1999) provided the operational practices of yard operations. This paper is useful to understand the yard operations in container terminals.

The research related to this paper is as follows; Chung *et al*.(1988) provided simulation analysis for a transtainer-based container handling facility. Taleb-Ibrahimi *et al*.(1993) analyzed the space-allocation problem of a constant or cyclic space requirement in container terminals. Castilho and Daganzo(1993) addressed the stacking problem of import containers in port container terminals. Kim and Kim(2002) proposed a method for determining the optimal size and number of storage space and yard cranes, respectively, for import container yards.

In the following section, the problem definition is suggested. In section 3, evaluation models for the container handling times of ATC are suggested. In section 4, evaluation models for the container handling times are suggested in considering the space allocation. In the final section, summary and conclusion are provided.

2. Problem Definition

<Figure 1> shows a container block in the yard in a container terminal. The shape of the container block can be represented by the values of length, width and height, (L, W ,H), which are specified by the numbers of bays, rows, and tiers in terms of the number of 20 feets containers. Note that the location of a specific slot may be specified by (bay, row, tier).

<Figure 2> shows an illustration of the container handlings of ATC in a bay. The storage space in the bay consists of tiers and rows.

<Figure 3> shows an illustration of an import container block with widthwise transfer points(BWTP). The transfer points at the sea-side of the block are used by yard tractors(YTs), which transport containers between the quay crane(QC) and the automated transfer crane(ATC). Note that the YTs may be traditional yard tractors or automated guided vehicles(AGVs). The transfer points at the land-side of the block are used by outside trucks(OTs). The containers on the block are handled by the ATC which can travel forwardly and backwardly along the block.

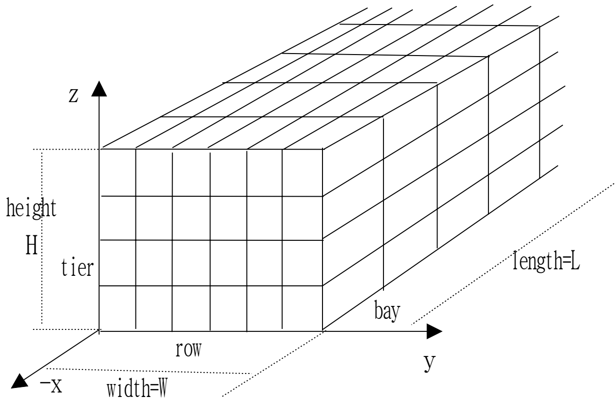


Figure 1. The container block in the yard in a container terminal.

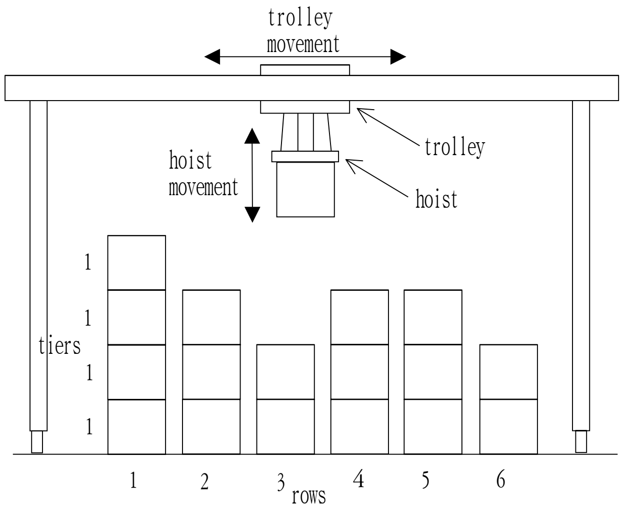


Figure 2. An illustration of the handling activities of an automated transfer crane(ATC).

There are two basic container handling operations of the ATC in the import container block with widthwise transfer points as shown in <Figure 3>: (1) In order to pick up a container from a YT and to stack it into a target slot of the import block, the ATC moves to a YT transfer point and picks up the container using its hoist. And then the ATC moves the container to the target bay while its trolley moves to the target row. Finally, the hoist of the ATC stacks the container at the target slot. (2) In

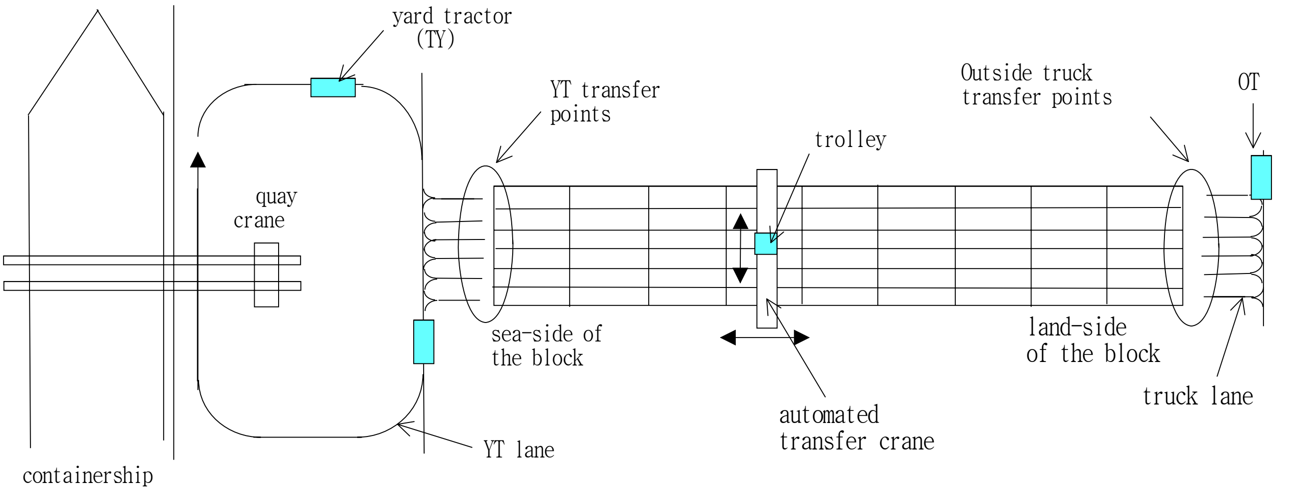


Figure 3. An illustration of the handling activities in case of an import container block with widthwise transfer points(BWTP).

order to deliver a container to an OT, the ATC moves to a target slot and picks up the container using its hoist. Then the ATC moves the container to the target OT transfer point while its trolley also moves to the OT transfer point. Finally, the hoist of the ATC loads the container onto the waiting OT.

<Figure 4> shows an illustration of an import container block with lengthwise transfer points(BLTP). The transfer points are arranged along the left or the right line of the block. Note that import container blocks and the berth may be vertical or parallel to each other. The import container block in <Figure 4> is parallel to the berth.

There are two basic container handling operations of the ATC in the import container block with lengthwise transfer points as shown in <Figure 4>: (1) In order to pick up a container from a YT and to stack it into a specific slot of the import block, the ATC moves to the transfer point(the target bay) while its trolley also moves to the transfer point(the right side of the block). And then the ATC picks up the container using its hoist. Then the trolley of the ATC moves the container to the target row. Finally, the hoist of the ATC stacks the container at the target slot. (2) In order to deliver a container to an OT, the ATC moves to the target bay while its trolley moves the target row. The ATC picks up the container using its hoist. Then the trolley of the ATC moves the container to the right side(the transfer point) of the block. Finally, the hoist of the ATC loads the container onto the waiting OT.

<Figures 5> and <Figures 6> show the illustrations of the traces of the movement of the trolley of ATCs corresponding to BWTP and BLTP as shown in <Figures 3> and <Figures 4>, respectively. Note that other alternatives for transfer points may be analyzed using the results of the analysis in this paper.

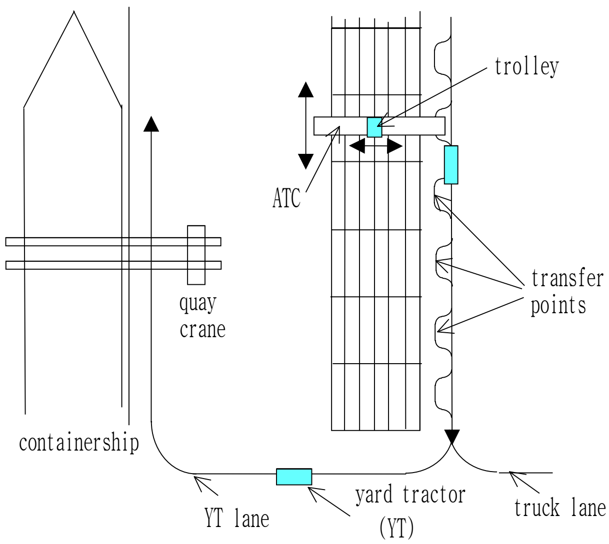


Figure 4. An illustration of the handling activities in case of an import container block with lengthwise transfer points(BLTP).

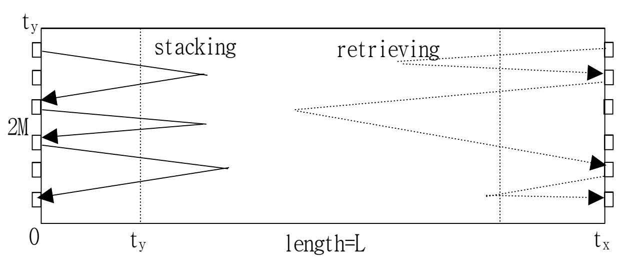


Figure 5. An illustration of the trace of the movement of the trolley of ATC in case of BWTP.

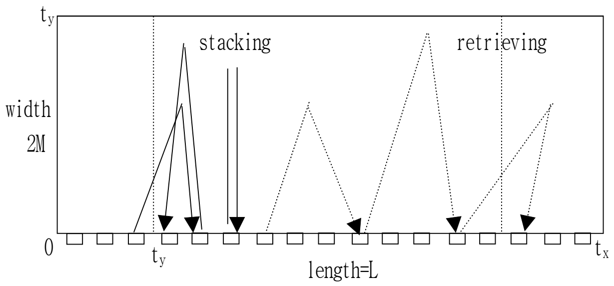


Figure 6. An illustrations of the trace of the movement of the trolley of ATC in case of BLTP.

The two following assumptions are introduced:
(1) For a block, one ATC is operated.
(2) The speeds of ATC, its trolley, and its hoist are constant and deterministic.

3. The Container Handling Times of Automated Transfer Crane

The following notations are used :

$L =$ the length of the block (the number of bays),

$M =$ the half of the width of the block (the half of the number of rows, 2M=W),

$H =$ the height of tiers of the block (the number of tiers),

$v_x =$ the speed of ATC at the direction of x (bays/hr),

$v_y =$ the speed of the trolley of ATC at the direction of y (rows/hr),

$v_z =$ the speed of the hoist of ATC at the direction of z (tiers/hr),

$t_x =$ the time required for ATC to travel from the left side to the right side of the block at the direction of x ($t_x = L/v_x$),

$t_y =$ the time required for the trolley of ATC to travel from one side of the width of the block to the other side at the direction of y ($t_y = 2M/v_y$),

$t_m =$ the time required for the trolley of ATC to travel from the center of the width of the block to the end of width at the direction of y ($t_m = M/v_y$),

$t_z =$ The time required for the hoist of ATC to travel from the top of the block to the bottom ($t_z = H/v_z$),

$p_{yt} =$ The positioning time of the hoist of ATC to a yard tractor

$p_{ot} =$ The positioning time of the hoist of ATC to an outside truck

$p_s =$ The positioning time of the hoist of ATC to a stack in the container block

$p_r =$ The positioning time to be required when repositioning one container

$E_W[T_S] =$ the expected cycle time of stacking operation of ATC in case of BWTP

$E_W[T_R] =$ the expected cycle time of retrieving operation of ATC in case of BWTP

$E_L[T_S] =$ the expected cycle time of stacking operation of ATC in case of BLTP

$E_L[T_R] =$ the expected cycle time of retrieving operation of ATC in case of BLTP

3.1 The container handling time in case of BWTP

Let x and y represent the travel times of the trolley of ATC at the direction of x and y, respectively. It is assumed that the travel time of the trolley of ATC from a transfer point to a stack in the block becomes the maximum value of travel times x and y. which is well known as the Chebyshev travel. Tompkins *et al.*(2003) explains the Chebyshev travel at the AS/RS with the single transfer point in the field of warehouse.

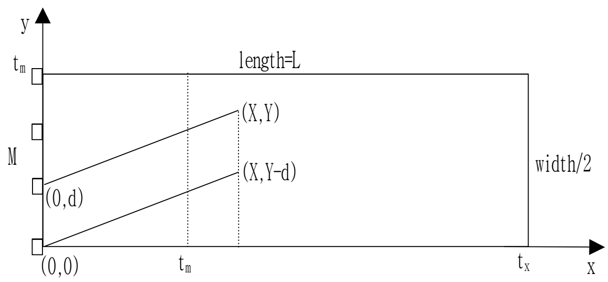


Figure 7. An illustration of the trace of the movement of the trolley of ATC in case of BWTP.

Let random variables X and Y be independent each other and follow uniform(0, t_x) and uniform(0, t_m), respectively. It is assumed that Z represents the time for the trolley of ATC to travel from transfer points (0, d) and a stack point (X, Y) in the block in terms of time as shown in <Figure 7>. Then, the time for the trolley of ATC to arrive the stack becomes

$$Z = \max(X, Y - d) \tag{1}$$

If the range of z is $0 \le z < t_m$-d, then F(z)=P(Z≤

z)=P(X≤z)P(Y-d≤z)=(z/t_x){(z+d)/t_m}. If the range of z is t_m-d≤z≤t_x, then, P(X≤z)=z/t_x and P(Y-d≤z)=1. Thus, F(z) becomes

$$F(z)=\begin{cases} z(z+d)/(t_x t_m) & 0 \le z < t_m - d \\ z/t_x & t_m - d \le z \le t_x \end{cases} \quad (2)$$

From F(z), the probability density function becomes

$$f(z)=\begin{cases} (2z+d)/(t_x t_m) & 0 \le z < t_m - d \\ 1/t_x & t_m - d \le z \le t_x \end{cases} \quad (3)$$

Note that the value of *d* itself follows uniform(0, t_y). In this paper, it is assumed that the value of *d* is set to be zero. Then, the expected time for the trolley of ATC to travel between a transfer point and stack point (X,Y) becomes

$$E(2Z)=\int_0^{t_m} 2z\frac{2z}{t_x t_m}dz + \int_{t_m}^{t_x} 2z\frac{1}{t_x}dz = t_x + \frac{t_m^2}{3t_x} \quad (4)$$

From now on, it is discussed how to evaluate the move times of the hoist and the trolley of ATC in a bay as shown in <Figure 8>. Let t_{yt}, t_{ot}, t_s and t_r set to be the move time at YT transfer points, the move time at OT transfer points, the move time at stacks, and the move time for rehandling containers including positioning times p_{yt}, p_{ot}, p_s and p_r, respectively.

Then, the move times of the hoist and the trolley of ATC in a bay including positioning times as shown <Figure 8> become

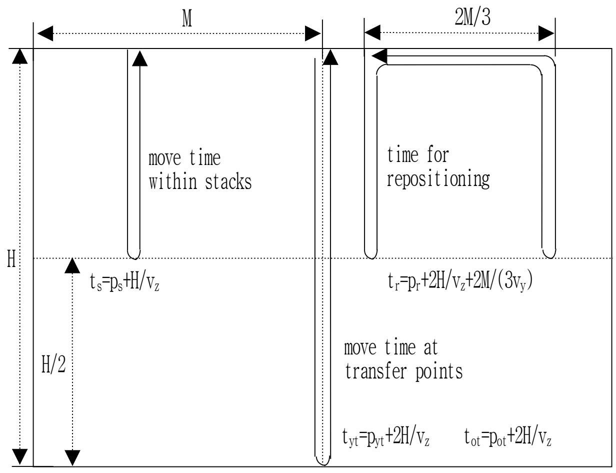


Figure 8. An illustration of container handlings in a bay in case of BWTP.

$$t_{yt}=p_{yt}+\frac{2H}{v_z} \quad (5)$$

$$t_{ot}=p_{ot}+\frac{2H}{v_z} \quad (6)$$

$$t_s=p_s+\frac{H}{v_z} \quad (7)$$

$$t_r=p_r+\frac{2H}{v_z}+\frac{2M}{3v_y} \quad (8)$$

Note that 2M/3 is the expected horizontal move distance of the trolley of ATC in a bay in order to rehandle a container; Let 2M set to be b. And let Z=|Y-X| where random variables X and Y are independent each other and follow uniform(0, b), respectively. Then, P(Z≤z)=P(|Y-X|≤z)=1-$(b-z)^2/b^2$. The probability density function of Z becomes f(z) =2(b-z)/b^2. Thus, E(Z)=b/3=2M/3.

<Table 1> summarizes the move times of the hoist and the trolley of ATC. Note that the speeds of the hoist and the trolley of ATC may change whether the hoist is loaded or empty. In that case, the move times of the hoist and the trolley of ATC are summarized at the right side of <Table 1>.

Table 1. The summary of the move times of the hoist of ATC in a bay including positioning times

	averaged move times	detailed move times
at YT transfer points	$p_{yt}+\frac{2H}{v_z}$	$p_{yt}+\frac{H}{v_z{}'}+\frac{H}{v_z{}''}$
at OT transfer points	$p_{ot}+\frac{2H}{v_z}$	$p_{ot}+\frac{H}{v_z{}'}+\frac{H}{v_z{}''}$
at stacks in the block	$p_s+\frac{H}{v_z}$	$p_s+\frac{H}{2v_z{}'}+\frac{H}{2v_z{}''}$
during repositioning a container	$p_r+\frac{2H}{v_z}+\frac{2M}{3v_y}$	$p_r+\frac{H}{v_z{}'}+\frac{H}{v_z{}''}+\frac{M}{3v_y{}'}+\frac{M}{3v_y{}''}$

v = the average speed of the hoist or the trolley
v' = the speed of the hoist or the trolley when the hoist is empty
v'' = the speed of the hoist or the trolley when the hoist is loaded

From equation (4), the travel time of the hoist of

ATC between a transfer point and (X,Y) becomes

$$E(2Z)=t_x+\frac{t_m^2}{3t_x}=\frac{L}{v_x}+\frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \quad (9)$$

From equations (5), (7) and (9), the expected cycle time for ATC to pick up import containers from YTs during the discharging time becomes

$$E_W(T_S)=p_{yt}+p_s+\frac{3H}{v_z}+\frac{L}{v_x}+\frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \quad (10)$$

From now on, it is discussed how to evaluate the expected cycle time for ATC to retrieve import containers. Firstly, it is needed to know the expected number of rehandles of containers at a bay to retrieve one container. Kim(1997) proposed an approximate formula, (H-1)/4+(H+2)/(16W), which estimates the number of rehandles in a bay in an import container block. He compared it with the index of selectivity(IOS) as shown <Figure 9-(a)>. The approximate formula depends on the status of the initial stacks of containers as shown in <Figure 9-(b)>.

The numbers in <Figure 9-(c)> may be considered as the possibility number of containers to be rehandled. When a container is retrieved, other containers on top of the container must be repositioned. When the number of containers in a bay is HW, the expected number of rehandles for retrieving one container becomes W{0+1+2+...+(H-2)+(H-1)}/(HW)=(H-1)/2. For example, if W=4 and H=5, then 4{0+1+2+3+4} /20=4/2=2. Thus, if the expected height(H/2) is given, the expected number of containers to be rehandled(ENOR) can be evaluated as follows.

$$E(R)=\frac{H/2-1}{2} \quad \text{where} \quad H\geq 2 \quad (11)$$

For example, the value of ENOR of the stacks in <Figure 9-(c)> can be obtained as follows; If equation (11) suggested in this paper is used, ENOR=(5/2-1)/2 =0.75. If the approximate formula proposed by Kim(1997) is used, ENOR=(2.5-1)/4+(2.5+2)/(16·4) =0.4453. Note that the true expected number of containers to be rehandled (true ENOR) is {2(0+1+2) +2(0+1)}/10 = 0.8. Thus, the ENOR in this paper is more accurate than the one proposed by Kim(1997) in the example. The strong point of the ENOR in this paper depends on only the current stacks of containers.

Thus, from equation (6), (7), (8) and (11), the expected cycle time for ATC to retrieve one import container becomes

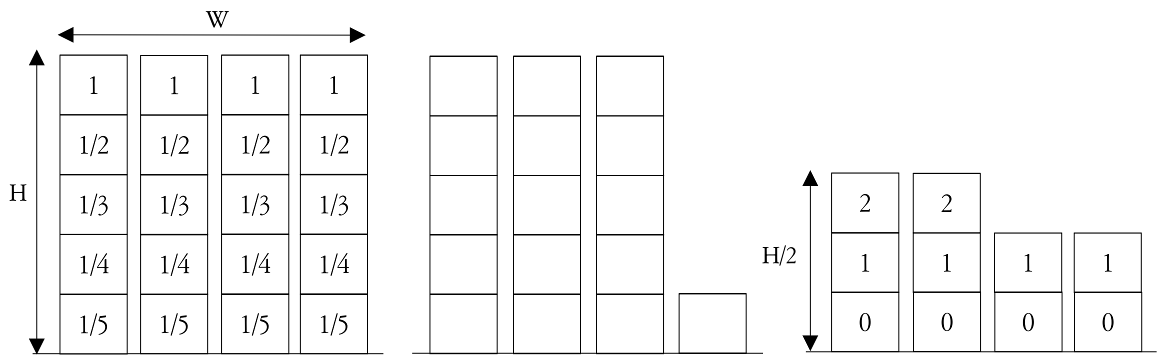
$$E_W(T_R)=p_{ot}+p_s+\frac{3H}{v_z}+\frac{L}{v_x}+\frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2}+\left(p_r+\frac{2H}{v_z}+\frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right) \quad (12)$$

3.2 The container handling times in case of BLTP

Let random variables X and Y be independent each other and follow uniform(0, t_x) and uniform(0, $2t_m$), respectively. It is assumed that Z represents the time for the trolley of ATC to travel from transfer point (c, 0) to a stack point (X, Y) in the block.

Then, the time for the trolley of ATC to travle from a stack point to a transfer point becomes

$$Z=\max(X-c,\, Y) \quad (13)$$



(a) Index of selectivity (b) An example of initial stack assumed in the approximate formula (c) Expected height for stack (a)

Figure 9. An illustration of the stacks inbound container.

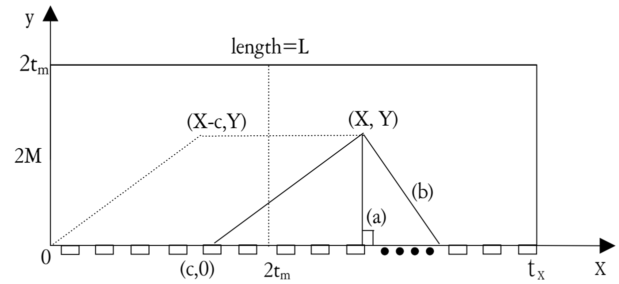


Figure 10. An illustration of the trace of the movement of the trolley of ATC in case of BLTP.

If the range of z is $0 \leq z < 2t_m$, then $F(z)=P(X-c \leq z)P(Y \leq z)=z(z+c)/(2t_xt_m)$. If the range of z is $2t_m \leq z \leq t_x-c$, then, $P(X-c \leq z)=(z+c)/t_x$ and $P(Y \leq z)=1$. Thus, F(z) becomes

$$F(z)=\begin{cases} z(z+c)/(2t_xt_m) & 0 \leq z < 2t_m \\ (z+c)/t_x & 2t_m \leq z \leq t_x - c \end{cases} \tag{14}$$

From F(z), the probability density function becomes

$$f(z)=\begin{cases} (2z+c)/(2t_xt_m) & 0 \leq z < 2t_m \\ 1/t_x & 2t_m \leq z \leq t_x - c \end{cases} \tag{15}$$

Note that the value of c itself follows uniform(0, t_x). In this paper, it is assumed that the value of c is set to be zero. Then, the expected time for the trolley of ATC to travel from a transfer point to a stack point (X,Y) becomes

$$\begin{aligned} E(Z) &= \int_0^{2t_m} z\frac{z}{t_xt_m}dz + \int_{2t_m}^{t_x} z\frac{1}{t_x}dz \\ &= \frac{t_x}{2}+\frac{2t_m^2}{3t_x} = \frac{L}{2v_x}+\frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \end{aligned} \tag{16}$$

The move times of the hoist and the trolley of ATC in a bay including positioning times can be obtained as shown in <Figure 11>. The move times in <Figure 11> are the same as the ones in <Table 1>.

Thus, if the trace of the movement of the trolley of ATC follows the form of <Figure 10-(a)>, the expected cycle time for ATC to pick up import containers from YTs during the discharging time becomes

$$\begin{aligned} E_L(T_S) &= p_{yt}+p_s+3\frac{H}{v_z}+\frac{L}{2v_x} \\ &+\frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2}+\frac{M}{v_y} \end{aligned} \tag{17}$$

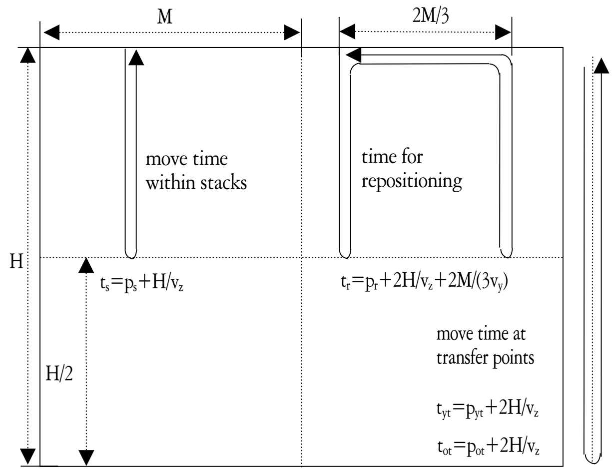


Figure 11. An illustration of container handlings in a bay in case of BLTP.

The expected cycle time of ATC to deliver one import container becomes

$$\begin{aligned} E_L(T_R) &= p_{ot}+p_s+\frac{3H}{v_z}+\frac{L}{2v_x}+\frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &+\frac{M}{v_y}+\left(p_r+\frac{2H}{v_z}+\frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right) \end{aligned} \tag{18}$$

Note that if the trace of the movement of the trolley of ATC follows the form of <Figure 10-(b)>, the expected cycle times to stack and to retrieve become as follows;

$$E_L(T_S)=p_{yt}+p_s+3\frac{H}{v_z}+\frac{L}{v_x}+\frac{4}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \tag{19}$$

$$\begin{aligned} E_L(T_R) &= p_{ot}+p_s+\frac{3H}{v_z}+\frac{L}{v_x}+\frac{4}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &+\left(p_r+\frac{2H}{v_z}+\frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right) \end{aligned} \tag{20}$$

<Table 2> summarizes the basic models to estimate the container handling times for the cases of BWTP and BLTP.

From the <Table 2>, the container handling times of ATC for BWTP and BLTP can be obtained. "Then, of the two BWTP and BLTP, which one is better?" This is a practical and important question. If we subtract equation (18) from (12) or equation (17) from (10), the we get the following;

$$I(L,M,H)=\frac{L}{2v_x}-\frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y}-\frac{M}{v_y} \tag{21}$$

Table 2. The summary of the models to estimate the container handling times

	The basic models
BWTP	$E_W(T_S) = p_{yt} + p_s + \frac{3H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2}$
	$E_W(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$
BLTP	$E_L(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \frac{M}{v_y}$
	$E_L(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \frac{M}{v_y} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$

If the value of I(L,M,H) is positive, then the BLTP is better than the BWTP at the aspect of container handling time. Otherwise, the BWTP is better than the BLTP.

Note that the equations in <Table 2> are the function of length, width and height, (L, 2M, H), which constitute the shape of a container block. Thus, these evaluation models for the container handling times of ATC can be used when designing various container block and determining specifications of ATC in container terminals.

A Numerical Example

The followings are assumed in this example; Firstly, M=5 and L=30, H=4, respectively. Secondly, the length, the width and the height of the slot of one TEU in the block is 6.5m, 3m and 3m, respectively. Thirdly, the speed of ATC, its trolley and its hoist are v_x=0.61TEU/sec(4m/sec), v_y=0.33TEU/sec(1m/sec) and v_z =0.40TEU/ sec(im/sec), respectively. Finally, positioning times for TYs(AGVs), OTs, stacks and stacks when rehandling are 10sec, 30sec, 6sec, and 10sec, respectively. When the example in this paper is designed, the practices in ECT and CTA provided by Saanen and Valkengoed(2005) are considered.

Using the equations in <Table 2>, the container handling times of ATC can be obtained as follows;

$$\begin{aligned} E_W(T_S) &= p_{yt} + p_s + \frac{3H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &= 10 + \left(6 + \frac{3\times 4}{0.4} + \frac{30}{0.61} + \frac{1}{3}\frac{0.61}{30}\frac{5^2}{0.33^2}\right) \\ &= 10 + 86.7 = 96.7(s) \end{aligned}$$

$$\begin{aligned} E_W(T_R) &= p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &+ \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right) = 30 \\ &+ 86.74 + \left(10 + \frac{2\times 4}{0.4} + \frac{2\times 5}{3\times 0.33}\right) \\ &\left(\frac{4/2-1}{2}\right) = 30 + 86.7 + 20.1 = 136.8(s) \end{aligned}$$

$$\begin{aligned} E_L(T_S) &= p_{yt} + p_s + 3\frac{H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &+ \frac{M}{v_y} = 10 + \left(6 + \frac{3\times 4}{0.4} + \frac{30}{2\times 0.61}\right. \\ &\left.+ \frac{2}{3}\frac{0.61}{30}\frac{5^2}{0.33^2} + \frac{5}{0.33}\right) = 10 + 78.9 \\ &= 88.9(s) \end{aligned}$$

$$\begin{aligned} E_L(T_R) &= p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} \\ &+ \frac{M}{v_y} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right) \\ &= 30 + 78.9 + 20.1 = 129.0(s) \end{aligned}$$

4. The container handling times in considering the space allocation

In general, import container blocks are used by import containers unloaded from multiple containerships. Thus, the import container block can be divided into several sections practically so that the import containers unloaded from different containership may be stacked at different sections of the block. To divide import container block into sections, a specific space is allocated to the import containers from a specific containership. This storage allocation affects the container handling times of ATC, which is discussed in this section.

4.1 The container handling time for BWTP in considering the space allocation

In case of BWTP in considering the space allocation, import containers are stacked at the ground slots of a specific region of an import container block during unloading time.

(1) In case that the land-side space is allocated

It is assumed that import containers are stacked at the ground slots in the range of [t_b, t_x] as shown in <Figure 12>.

Let random variables X and Y be independent each other and follow uniform(0, t_x-t_b) and uniform(0, t_x-t_b), respectively. Note that Y follows uniform(0, t_x-t_b). Let Z=max(X,Y). Then, the range of z becomes $t_b \le z \le t_x$, and $P(Z \le z)=P(X \le z)P(Y \le z)$. Thus, F(z) becomes

$$F(z) = \frac{z^2}{(t_x - t_b)^2} \quad t_b \le z \le t_x \tag{22}$$

From F(z), the probability density function becomes

$$f(z) = \frac{2z}{(t_x - t_b)^2} \quad t_b \le z \le t_x \tag{23}$$

Then, in <Figure 12>, the expected time of the trolley of ATC to travel between a YT transfer point and stack point (X,Y) becomes

$$\begin{aligned} E(2Z) &= \int_{t_b}^{t_x} 2z \frac{2z}{(t_x - t_b)^2} dz \\ &= \frac{4}{3}(t_x^2 + t_x t_b + t_b^2) \end{aligned} \tag{24}$$

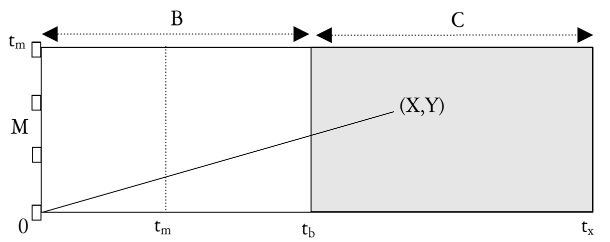


Figure 12. An illustration that the land-side space is allocated.

(2) In case that the sea-side space is allocated

It is assumed that import containers are stacked at the ground slots in the range of [0, tb] as shown in <Figure 13>. Suppose that tb be the time required for ATC to travel from the left side to the right side of a virtual block. Then, the analysis for this case is the same as the one for the case of BWTP in section 3.1. Thus, the expected time of the trolley of ATC to travel between a YT transfer point and stack point (X,Y) becomes

$$E(2z) = t_b + \frac{t_m^2}{3t_b} \tag{25}$$

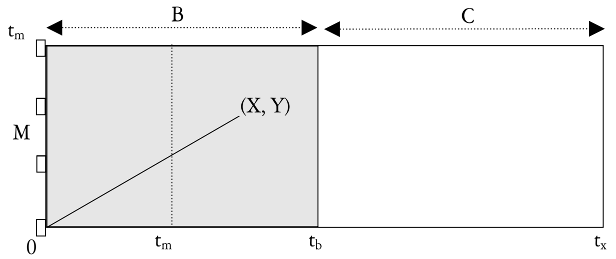


Figure 13. An illustration that the sea-side space is allocated.

(3) In case of the randomized storage

It is assumed that import containers are stacked at randomly selected bays as shown in <Figure 14>. Note that the analysis for this case is the same as the one for the case of BWTP in section 3.1. Thus, the expected time of the trolley of ATC to travel between a YT transfer point and stack point (X,Y) becomes

$$E(2z) = t_b + \frac{t_m^2}{3t_x} \tag{26}$$

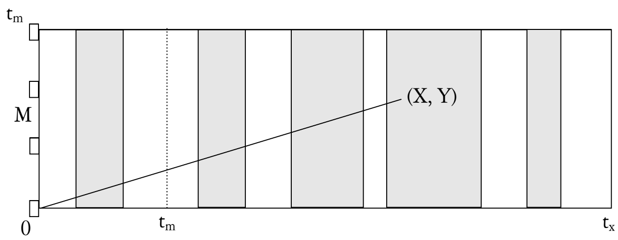


Figure 14. An illustration of the randomized storage.

<Table 3> summarizes the models to evaluate the container handling times for BWTP given space allocation. In case of the land-side section storage, $E_W(T_S)$ is the sum of the travel time including positioning times in a bay and equation (24). $E_W(T_R)$ is obtained by adjusting the analysis for the case of BWTP in section 3.1 to OT transfer points of the block as shown in <Figure 12>. In case of the sea-side section storage, $E_W(T_S)$ is obtained using equation (10). $E_W(T_R)$ is obtained by adjusting the results of

the land-side section storage to the OT transfer points of the block as shown in <Figure 13>. In case of randomized selected bay storage, $E_W(T_S)$ and $E_W(T_R)$ are the same as the equation (10) and (12), respectively.

Table 3. The models to evaluate the container handling times for BWTP given space allocation

	Evaluation equations for BWTP given space allocation
land-side section storage	$E_W(T_S) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{4}{3v_x^2}(L^2 + BL + B^2)$
	$E_W(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{C}{v_x} + \frac{1}{3}\frac{v_x}{C}\frac{M^2}{v_y^2} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$
sea-side section storage	$E_W(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{B}{v_x} + \frac{1}{3}\frac{v_x}{B}\frac{M^2}{v_y^2}$
	$E_W(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{4}{3v_x^2}(L^2 + CL + C^2) + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$
randomly selected bay based storage	$E_W(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2}$
	$E_W(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{v_x} + \frac{1}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$

4.2 The container handling time for BLTP in considering the space allocation

In case of BLTP in considering the space allocation, import containers are stacked at the ground slots of a specific region of import container block during unloading time. It is assumed that import containers are stacked at the ground slots in the range of B[t_1, t_2] as shown in <Figure 15>.

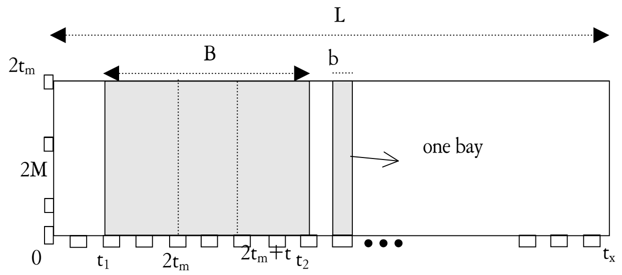


Figure 15. In case that import containers are stacked at the bays in section B.

Table 4. The models to evaluate the container handling times for BLTP given space allocation

	Evaluation models for BLTP given space allocation
B=L, block allocation	$E_L(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \frac{M}{v_y}$
	$E_L(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{L}{2v_x} + \frac{2}{3}\frac{v_x}{L}\frac{M^2}{v_y^2} + \frac{M}{v_y} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$
2tm<B<L, Section allocation	$E_L(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{B}{2v_x} + \frac{2}{3}\frac{v_x}{B}\frac{M^2}{v_y^2} + \frac{M}{v_y}$
	$E_L(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{B}{2v_x} + \frac{2}{3}\frac{v_x}{B}\frac{M^2}{v_y^2} + \frac{M}{v_y} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$
B=b, bay allocation	$E_L(T_S) = p_{yt} + p_s + 3\frac{H}{v_z} + \frac{2M}{v_y}$
	$E_L(T_R) = p_{ot} + p_s + \frac{3H}{v_z} + \frac{2M}{v_y} + \left(p_r + \frac{2H}{v_z} + \frac{2M}{3v_y}\right)\left(\frac{H/2-1}{2}\right)$

In case that the value of B is L, which means that containers are stacked at randomly selected bays, the models were discussed in section 3.2. In the case the range of B is $2t_m$<B<L, which implies that a section of the block is allocated to the containers from a

specific containership, the analysis for this case is also the same as the one for the case of BLTP in section 3.2. In case that the value of B is b, which implies that a bay of the block is allocated to specific containers, the expected travel time of the trolley of ATC in a bay is $2M/v_y$, because no Chebyshev travel occurs. Thus, considering the analysis results of section 3.2 and <Table 2>, <Table 4> can be easily obtained from <Figure 15>.

5. Summary and Conclusions

In this paper, the container handling times of automated transfer cranes(ATCs) at import container blocks with widthwise transfer points(BWTP) and import container blocks with lengthwise transfer points(BLTP) were analytically determined, respectively. For the two basic alternatives of import container blocks, the models to estimate various motion times of stacking and retrieving operations of ATC were suggested. Also, the models to estimate the container handling times of ATC were suggested in considering the space allocation. Since the models in this paper are the functions of the block shape and the transfer point configuration, it is possible to analyze how the block shape and the transfer point configuration affect the container handling times of ATC.

The models of this paper may be useful when estimating the container handling times, designing import container block and determining the specifications of ATC in yards in container terminals.

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김 기 영
부산대학교 산업공학과에서 학사, 석사, 박사
현재 : 동서대학교 국제관계학부
물류유통학전공 부교수
관심분야 : 물류시스템