Double Container-handling Operation for an Efficient Seaport Terminal System

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Abstract. For an efficient seaport terminal, we propose a novel operational model, namely, a double container-handling operation among operating machines, such as automated guided vehicles (AGVs), automated transfer cranes (ATCs), and quay container cranes (QCCs), in a seaport terminal system. In addition, a passing lane is provided in a container storage yard in order to activate the container-handling operation by the AGVs and ATCs. In this paper, the effect of the double container-handling operation and passing lane on the system utilization is examined. Finally, the effectiveness of the proposed operational model with a passing lane is discussed on the basis of the operating time and obtained number of operating machines for a given demand in consideration of a mega-container terminal.

Keywords. Double container handling, seaport terminal system, AGV, QCC, ATC

Introduction

In recent years, the volume of container trade at worldwide seaport terminals has increased significantly [1]. In this regard, it is required to promote the automation and improvement of a container-handling operation in a seaport terminal system. The authors have, so far, achieved the following design challenges in terms of the development of highly efficient and automated container-handling systems: for given demands, (I) combinations of the minimum number of operating machines were found [2]; (II) an efficient system layout was identified [3]; (III) operational models for machines were developed [4,5]; (IV) and (V) the machine performance and reliability were determined [6,7]. Moreover, we are currently developing efficient operational models for a case in which operating machines are in a maintenance mode in consideration of their reliability [8]. In addition to our research, many studies have focused on seaport terminal systems [9].

Previous studies have primarily taken into account import containers. Accordingly, the containers imported by a containership were transported to a terminal storage yard before being forwarded to other locations (i.e., containership → terminal system). How-

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ever, in an actual seaport terminal, export containers from a terminal to a containership also have to be included.

As for the present import and export container-handling operation at seaport terminals in Japan, first, import containers are all unloaded into a terminal system from a containership. After that, export containers in the terminal system are loaded onto the containership. Hence, a container transport vehicle cannot avoid traveling without containers on the outbound or homeward trek when making a round trip from a quay side to a storage yard in a terminal system. In this paper, we define the conventional operation as a single container-handling operational model. For this conventional operational model, in order to reduce the vehicle empty travel, we propose a novel operational model, namely, a double container-handling operation performed by operating machines in the terminal system. By using the proposed operational model, import and export containers are loaded and unloaded in the quay and storage yard at the same time. Furthermore, we provide a passing lane in the storage yard to activate the container-handling operation by container transport vehicles and movable container storage cranes.

Regarding the multi-item or container-handling operation, studies that deal with automated manufacturing systems, for example, that by Liu *et al.*, have used multi-load vehicles and addressed the task allocation problem [10]. On the other hand, usage of such a multi-load vehicle in a seaport container terminal has been considered by Grunow *et al.* only [11]. However, these studies have addressed the vehicle dispatching problem as a main topic, and, thus, the effect of a container-handling operational model on utilization of the system resources such as operating machines has not been investigated.

Therefore, in order to examine the effect of the double container-handling operational model on the system utilization, we compare the systems with the use of the (I) conventional and (II) proposed operational models on the basis of the operating time for a given task. Moreover, we impose a demand on the terminal system in consideration of the realization of a mega-container terminal in Japan. We then develop the systems and compare the obtained number of machines. Finally, we discuss the effectiveness of the proposed operational model.

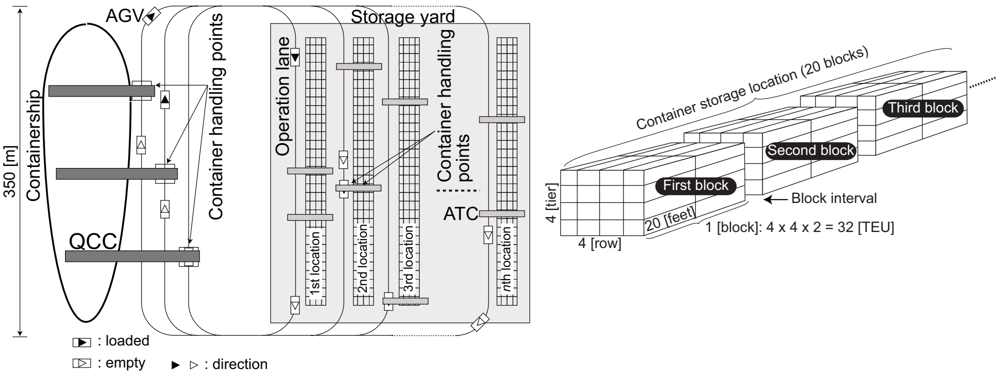
1. Container-handling System in a Seaport Terminal

1.1. System Setting

Fig. 1 shows a horizontal container-handling system in a seaport terminal, which is the objective of this paper. The effectiveness of the system, compared to a vertical one, has been shown by controlling operating machines efficiently [3]. In a seaport terminal system, as shown in Fig. 1, quay container cranes (QCCs), automated guided vehicles (AGVs), and automated transfer cranes (ATCs) are used for container handling.

1.1.1. System layout

Fig. 1(a) shows one berth of the container-handling system in a seaport terminal. In this paper, the width of one berth is 350 [m] to respond to a cargo-carrying vessel. The depth of the berth is generally about 500 [m] in domestic terminals; however, the scale is variable according to the number of container storage locations in a yard.



(a) Terminal system layout and containership (one berth, top view)

(b) Container storage location that consists of blocks, rows, and tiers

Figure 1. Horizontal Container-Handling System with AGVs, ATCs, and QCCs in a Seaport Terminal

1.1.2. Container storage location

A container storage location arranged in the yard is shown in Fig. 1(b). One location consists of blocks. One block has 32 (4 tiers $\times$ 4 rows $\times$ 2 (20-foot equivalent)) container storage spaces; in other words, the maximum storage height and width are those determined by the height and width of four containers. In this paper, we assume that one location consists of 20 blocks with a 3 [m] interval. This assumption is given considering general domestic seaport terminals.

1.2. Operating Machines and Machine Performance

As shown in Fig. 1(a), the QCCs for container loading and unloading at the quay side, the ATCs for container transfer, storage, and unloading in the storage yard, and the AGVs for container transport between the quay side and storage yard are the operating machines in this terminal system. The number of QCCs, AGVs, and ATCs are the input parameters for a container-handling simulation. Here, three QCCs are operating in the quay side because the scale of the berth is fixed (width = 350 [m]). As for the number of ATCs, two ATCs operate at one storage location in the yard.

The performance of the operating machines is as follows: for the AGV, the max. container transport and cornering velocities are 5.56 and 1.39 [m/s], respectively; the max. empty traveling and cornering velocities are 6.94 and 2.78 [m/s], respectively [12]; the acceleration and deceleration are 0.15 and 0.63 [m/s^2], respectively, regardless of the container-loaded or empty state. The max. ATC moving velocity is 2.5 [m/s]; the acceleration and deceleration are 0.1 and 0.4 [m/s^2], respectively [12]; the cycle time of one container transfer and storage or unloading and transfer operations is 135 $\sim$ 150 [s]. The cycle time of the QCC container loading or unloading operation is 90 [s]. These cycle times are given on the basis of average data of actual terminal systems in Japan: in an hour, 24 $\sim$ 30 containers are handled by an ATC and 90 containers are handled by a QCC.

1.3. Single Container-handling Operational Model

In general, import containers are first unloaded from a containership onto a storage yard; afterward, export containers are loaded from the yard onto the containership using single container handling, that is, the conventional operational model. The detailed operation procedures are described as follows:

1. QCCs unload import containers, which will be transported by AGVs, from a containership onto the AGVs. After all of the import containers are unloaded, the QCCs begin to load export containers from the AGVs onto the containership.
2. The AGVs transport the import containers from the quay side to target storage locations in the yard. For export containers, the AGVs travel from the quay side to locations without containers.
3. An AGV transfers an import container to an ATC that is available at a location. After all the import containers are transferred, an ATC transfers an export container from one location to an incoming AGV.
4. The AGV that has completed the container transfer goes back to a QCC (without a container). On the other hand, the AGV that has received the export container transports it to a QCC, that is, the containership.
5. ATCs unload the import containers from the AGVs and store them into the storage locations. On the other hand, the ATCs load the export containers from the locations onto the AGVs.

2. Double Container-handling Operational Model

2.1. Cycle of Operation

Fig. 2 illustrates a cycle of the double container-handling operational model between the quay (containership) and storage yard (location). The left side of the figure depicts the container loading and unloading operations in the quay, the right side depicts the container transfer, storage, and unloading operations in the yard, and the middle depicts the container transport operation by the AGV.

After an AGV arrives at a QCC, an export container that was transported from the storage yard is unloaded onto a containership by the QCC taking a constant amount of time. Right after the QCC finishes the unloading operation, it begins to load an import container from the containership onto the AGV taking a constant amount of time as well. The AGV transports the container to a designated area in the storage yard. As in the operation at the quay side, the container is transferred to an ATC from the AGV and then stored at a location by the ATC taking a constant amount of time. Afterward, an export container is unloaded and transferred to the AGV by the ATC taking a constant amount of time. The AGV begins to transport the container to the containership (a QCC). Thus, the AGVs are able to achieve the container transport without traveling with an empty load by handling containers twice in the quay and yard.

Regarding other operational models, we adopt the following models, which have been shown to be an efficient management strategy in a seaport terminal system. For import containers, the container-handling tasks are evenly divided among three QCCs; the containers are planned to be evenly transported to each storage site. For export as well

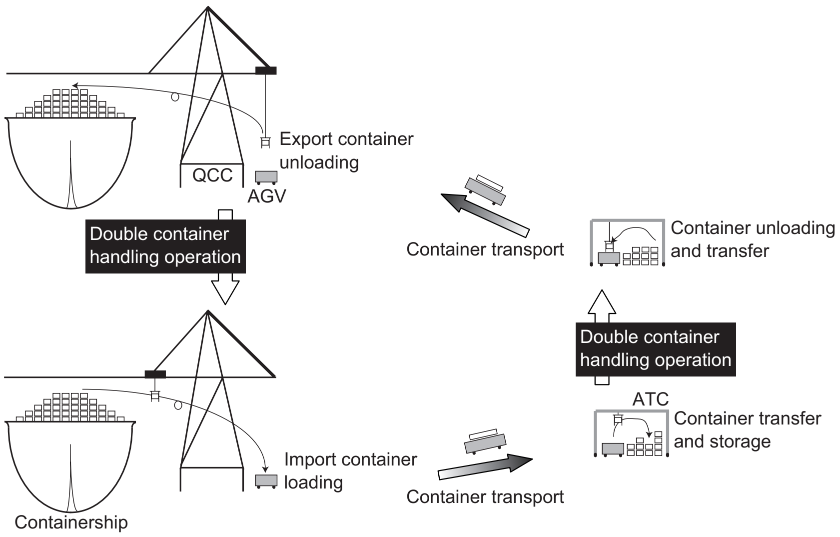


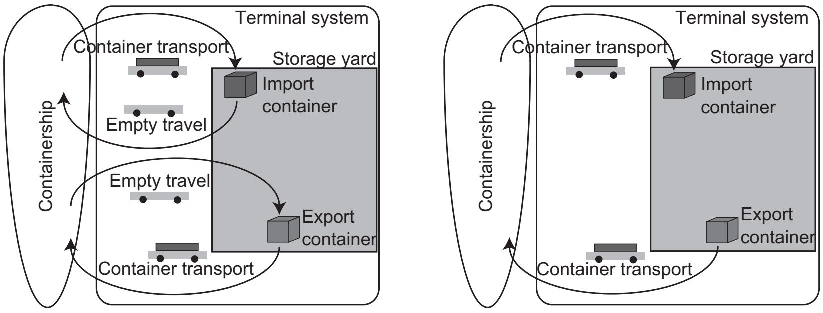
Figure 2. Cycle of the Double Container-handling Operation by a QCC, an AGV, and an ATC

as import containers, the tasks are evenly divided from each storage site. The containers are to be transported to three QCCs evenly. The execution sequence of the planned containers is scheduled so that the total distance of the ATCs for container handling is minimized. In the storage yard, an AGV calls out an ATC on the basis of the workspace-based ATC selection rule right after the AGV enters an operation lane. The detailed operational models are described in the literature [4,5].

2.2. Single and Double Container-handling Operations

As shown in Fig. 3, the single and double container-handling operational models have the following characteristics regarding the operational time among the machines and the empty travel of the AGV.

- Single container-handling operational model: All import containers are first unloaded from a containership into a terminal system; after that, export containers in a storage yard are loaded from the system onto the containership (see Fig. 3(a)).
  - ∗ The container-handling operations in the quay and storage yard among the AGVs, QCCs, and ATCs require "one-container" handling time.
  - ∗ The AGVs make the rounds in the system "n" times equal to the total number of import and export containers. Here, one half of them are the empty trips.
- Double container-handling operational model: Import and export containers are unloaded and loaded simultaneously in the quay and yard (see Fig. 3(b)).
  - ∗ The container-handling operations in the quay and storage yard among the AGVs, QCCs, and ATCs require "two-containers" handling time.
  - ∗ The AGVs make the rounds in the system "$\frac{n}{2}$" times. In other words, the AGV transports a container between the quay and storage yard on the outward and homeward trips.



(a) Single container-handling operational model

(b) Double container-handling operational model

Figure 3. Comparison of the Cycles of the Single and Double Container-handling Operation Models

2.3. Passing Lane

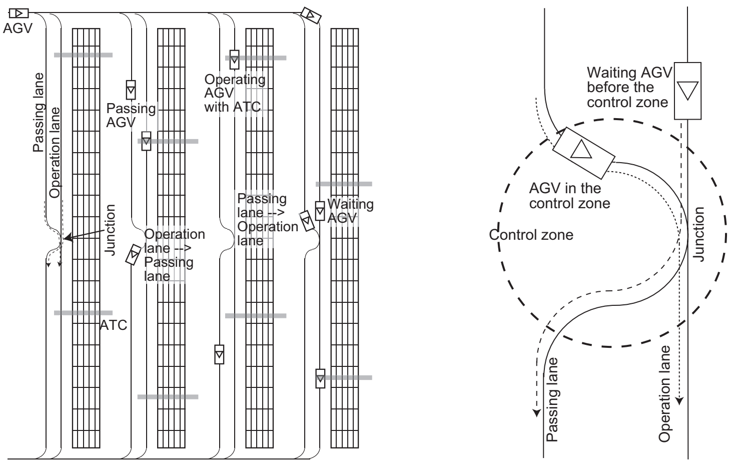
As described in 2.2, compared to the single container-handling operational model, although the double container-handling operational model halves the number of AGV trips with empty loads, the operational model doubles the container-handling time among the AGV, QCC, and ATC. In this paper, it is assumed that the number of QCCs at the quay is three, but the number of ATCs in the storage yard increases or decreases according to the number of locations. However, in a case in which an AGV stopped for container handling with an ATC impedes the container transport of other AGVs even if the number of locations (ATCs) is increased, the efficiency of the operation in the yard might be decreased.

To solve this problem, we additionally provide one adjacent passing lane for each operation lane, as shown in Fig. 4(a). The passing and operation lanes cross at the middle of the storage location. When an AGV goes into the storage yard, it selects either the passing or the operation lane according to its destination (upper or lower half of a location). An AGV that finished a container-handling operation at the upper half of the location goes to the junction; then, it changes lanes to the passing lane; finally, it leaves the yard to go to the quay. On the other hand, an AGV that operates with the ATC at the lower half of the location changes from the passing lane to the operation lane at the junction. In the vicinity of the junction, a control zone is installed, as shown in Fig. 4(b). Hence, in the control zone, the AGV that entered first has priority over other AGVs to go through the zone. Thus, collision avoidance for the AGVs at the junction is ensured.

3. Simulation Experiment

3.1. Simulation Scenario

Since the total number of import and export containers handled in the terminal system is the same even if the container flow between the terminal system and inland is considered, as described in [13,14], only the container flow between a containership and the termi-



(a) Provided passing lanes adjacent to the operation lanes

(b) Control zone around the junction

Figure 4. Behavior Model in the Container Storage Yard with the Provided Passing Lanes

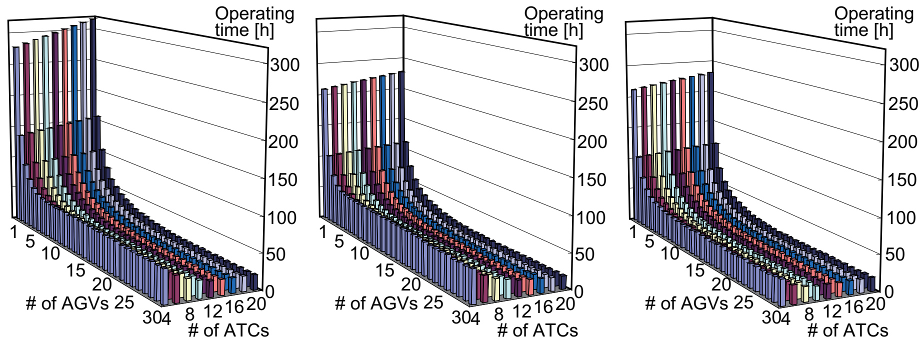
nal system is considered in this simulation. As a simulation scenario, we assume that a cargo-carrying vessel that has 10,000 [TEU (Twenty-foot Equivalent Unit)] containers comes in. From our field surveys, we have found out that about 2,000 [TEU] containers in the vessel, at a maximum, are handled. Therefore, in the simulation experiment, the operating machines handle 2,000 containers. Half of the containers, i.e., 1,000, are import containers, and the other half, i.e., 1,000, are export containers. Here, as described in 1.1.2, since one location has container storage space of up to $32 \times 20 = 640$ [TEU] only, two locations, i.e., at least four ATCs, are used in the system. All combinations of three QCCs (fixed), 1 $\sim$ 30 AGVs, and 4 $\sim$ 20 ATCs represent the input parameter for the container-handling simulation.

Under the given scenario, the following three systems are prepared for the simulation to examine the effect of the double container-handling operation model on terminal system utilization. These three systems are then compared and evaluated on the basis of the operating time for 2,000 containers (tasks). The operation time between the AGV and ATC in the storage yard with the use of the single and double handling operation models is 135 [s] (single) and $150 \times 2 = 300$ [s] (double). This is because, in the system with the double container-handling model, it is not always true that an export container is located in the same block in which an import container will be stored.

1. Single handling with one operation lane (conventional system **1**)
2. Double handling with one operation lane (proposed system **2**)
3. Double handling with one operation and passing lanes (proposed system **3**)

3.2. Comparison Result of the Operating Time

Fig. 5 shows the operating time of three systems with QCCs, AGVs, and ATCs for 2,000 tasks. From the results of Fig. 5(a) $\sim$ Fig. 5(c), the operating time for all systems in-



(a) Conventional system 1 (b) Proposed system 2 (c) Proposed system 3

Figure 5. Comparison Results of the Operating Time for 2,000 Container-handling Tasks

creases as the number of ATCs increases for a few AGVs. This is because the number of locations increases as the number of ATCs increases; eventually, the total container transport distance of the AGVs increases. From this result, it is noteworthy that a system with few AGVs and many ATCs might be inefficient.

From the comparison of Fig. 5(a) with Fig. 5(b), regardless of the number of ATCs, the operating time of the proposed system with few AGVs (e.g., $1 \sim 5$) decreased in all cases. The reason for this result is that the empty trips of the AGVs using the single container-handling model have more harmful effects on system utilization than the heavy workload caused by the AGVs using the double container-handling model. The difference in the operating time of those systems with few ATCs ($4 \sim 14$), however, decreases as the number of AGVs increases. This result indicates that the double container-handling operation with many AGVs causes a heavy workload in a case in which there are few locations; thus, the operation model eventually has harmful effects on system utilization. A comparison of system 2 in Fig. 5(b) with system 3 in Fig. 5(c), in which the passing lane is additionally provided, shows that the workload caused in system 2 is eased in system 3. As a result, the container-handling operation in the storage yard was fully activated; furthermore, the operating time of system 3 with $4 \sim 14$ ATCs decreased as the number of AGVs increased.

The average reduced operating time (the sum of the difference of the operating time / number of simulation runs) of system 2 is 8.01 [h] less than in system 1, and that of system 3 is 3.79 [h] less than in system 2. These results show the effect of the proposed double container-handling operation model and the passing lane on system utilization.

3.3. The Mega-Container Terminal

3.3.1. Problem description

Major seaport data in Japan in 2006 are described in Table 1. These seaports are identified as "super hub ports," according to the concept of a mega-container terminal proposed by the Ministry of Land, Infrastructure, Transport and Tourism of Japan. In the table, although the Yokohama Minami-Honmoku terminal consists of only two berths, its re-

Table 1. Major seaports in Japan aiming at a mega-container terminal

Port name	Number of berths	Annual volume [TEU]
Yokohama (Minami-Honmoku)	2	863,000
Tokyo (Ohi)	7	2,098,000
Nagoya (Tobishima)	1	266,000
Kobe (Port island)	6	1,061,000

Table 2. Combination of a number of AGVs and ATCs that meets the demand 68.49 [container/hour]

System number	# of AGVs	# of ATCs (locations)
1 (conventional system)	13	10 (5)
with single handling and one operation lane	12	12 (6)
2 (proposed system)	11	10 (5)
with double handling and one operation lane	10	12 (6)
	9	14 (7)
3 (proposed system)	11	6 (3)
with double handling and one operation	10	8 (4)
and passing lanes	9	10 (5)

cent annual container volume (in 2007) reached 1,000,000 [TEU], a remarkable number. Therefore, as in the Minami-Honmoku terminal, we aim at developing a terminal system that achieves a volume of 500,000 [TEU] annual containers per berth.

We assume that the automated container-handling system works 365 days a year and 24 hours a day. Generally, since a cargo-carrying vessel takes several hours to come in and sail out in addition to the maintenance time for the operating machines, in an actual seaport terminal, the daily working time of the system is 20 hours. Thus, we developed a system that meets a required throughput, $500,000/(365 \times 20) \simeq 68.49$ [container/hour], to achieve the handling of 500,000 containers per year per berth.

3.3.2. Comparison result of the obtained number of AGVs and ATCs

Combinations of the number of AGVs and ATCs that meet a required throughput, i.e., demand 68.49 [container/hour], are derived from Fig. 5 and shown in Table 2. In the table, note that a system with more AGVs and ATCs than mentioned meets the demand. Furthermore, in Table 2, combinations of the number of AGVs and ATCs are not mentioned, in which case the number of AGVs does not decrease for more ATCs. For instance, as for system 1, although a system with 12 AGVs and 14 ATCs meets the demand, the combination is not mentioned.

Regarding the results of systems 1 and 2, the number of AGVs obtained in system 2 with 10 and 12 ATCs was lower than that of system 1. Moreover, system 2, which consists of 9 AGVs and 14 ATCs, also met the demand. As for system 3, in which the passing lane was provided, even when the number of ATCs was 6 or 8, the system was able to meet the demand with 11 or 10 AGVs. Additionally, although the obtained number of AGVs in systems 1 and 2 with 10 ATCs was 13 and 11, respectively, the number of AGVs in system 3 was 9 and met the demand.

From the results, it is noticeable that the double container-handling operation model and the addition of the passing lane are also effective for high system utilization in terms of the realization of the mega-container terminal. Therefore, we confirm the effectiveness of the proposed operation model with the passing lane.

4. Conclusion and Future Work

In this paper, we proposed a novel operation model, which is double container handling among AGVs, QCCs, and ATCs for an efficient seaport terminal. Furthermore, in order to activate the operation among AGVs and ATCs in a container storage yard, we provided a passing lane in addition to the operation lane. Through simulation experiments, we demonstrated the effect of the double container-handling operation and the passing lane on system utilization. Furthermore, three systems were developed and considered for the realization of a mega-container terminal in Japan. From these results, we confirmed the effectiveness of the proposed operation model with the passing lane.

In future works, we will take into account the following issues which were the given assumptions in this paper: (I) variable operation time among the operating machines according to a container stacking condition and (II) trade-off analysis between the number of passing lanes and junctions (control zones) and the container storage yard space. Moreover, we will tackle a challenge, that is, the optimization of container-shuffling operations both on-ship and in-yard for more efficient seaport terminal systems.

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