

# Optimal Design, Evaluation, and Analysis of AGV Transportation Systems Based on Various Transportation Demands

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**Abstract**— In this paper, two designs for optimal Automated Guided Vehicle (AGV) transportation systems are presented. One is vertical and the other, horizontal. For these systems, the hybrid design methodology proposed here is used. Therefore, we describe how to model and formulate these transportation systems and derive the design parameters, that is, the optimal design solutions. We next evaluate these two transportation systems based on the various transportation requirements, that is, the demands from a port authority. For this purpose, we compare the systems based on the total costs in constructing them. Finally, the evaluation and analytical results are provided, and the most convenient system is presented based on the validity of each system for the given demand.

**Index Terms**— AGV transportation system, optimal and hybrid design methodology, evaluation, analysis.

## I. INTRODUCTION

The explosive growth in recent years in the volumes of freight has resulted in heavier workloads at seaports. Port authorities are being urged to implement advanced technologies to accommodate the increasing number of container ships. In this regard, the implementation of an Automated Guided Vehicle (AGV) transportation system would effectively automate a port container terminal. The advantages of implementing such a system are as follows: it would save the port terminal space; it would be more cost effective; and it would increase the efficiency. Literature is available to support these ideas [1] [2]. Although there are some conceivable types of AGV transportation systems, in this paper, we address two typical and prevalent AGV transportation systems for comparison, which are illustrated in Fig.1. We first design the systems optimally within the limited operation rules guiding mobile machines, that is, autonomous agents; then, the most convenient system is presented after evaluating the validity of the optimally designed systems.

In the general design process, various design parameters for the various transportation demands need to be derived fast and optimally. Additionally, the agent's behavior in the system needs to be analyzed. Moreover, the most convenient system should be identified on the basis of careful evaluation if there are some transportation systems as candidates. To meet these requirements, some challenging

points are as follows:

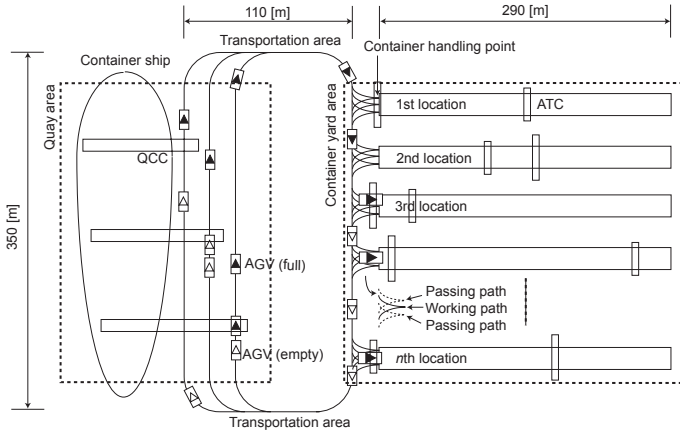
1. How can a system be designed that will solve the combinatorial optimization problems inherent in a heterogeneous multi-agent transportation system fast and optimally?
2. How can a system be evaluated and analyzed to ascertain that it is valid and effective to meet the demands?

Two methodologies are being proposed for the first challenge point above. One is based on a numerical model, and the other, on a simulation. On the other hand, to solve the second challenge point, the systems are compared and evaluated with the use of a deterministic design.

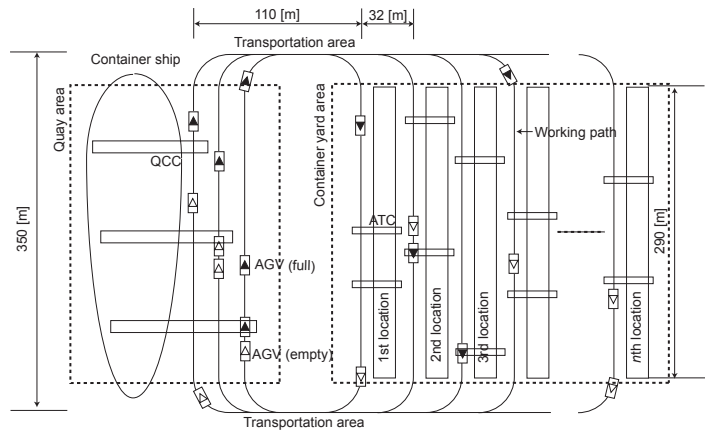
With regard to a numerical design methodology, Abe *et al.* [3] [4] proposed the use of an open queuing network model. However, it is impossible to consider the gap between the numerical model and the behavior of an actual agent, for example, the existence of congestion in the system. On the other hand, Chiba *et al.* [5] proposed an integrated design methodology that incorporates a Genetic Algorithm (GA) in a simulation-based approach. However, several hours, that is, a significant amount of computational time, are needed in the search for the optimal design parameters. Additionally, with each changed design parameter, it is impossible to analyze the global system behavior numerically by this methodology. To solve these problems, Hoshino *et al.* [6] have proposed a hybrid design methodology that uses a closed-cyclic queuing network model and a simulation-based optimization method. In this study, to overcome the first challenge point, we apply the proposed methodology for the optimal design of the system because of the following advantages:

- It is possible to design the system optimally within a few minutes.
- It is possible to consider and numerically analyze the gap and the global system behavior.

In their research relating to the comparison and evaluation of transportation systems, Chin *et al.* [7] have evaluated various transportation systems based on the construction cost. However, the optimality of the system is not considered because every design parameter is decided



(a) The vertical AGV transportation system



(b) The horizontal AGV transportation system

Fig. 1. Two types of AGV transportation systems (top view)

by the deterministic parametric approach and the systems are just compared with regard to a particular transportation requirement because a significant amount of time is required for the design process. On the other hand, one other study has compared the two types of AGV transportation systems (Hoshino *et al.* [8]). In this study, the transportation time by each system was considered, and the characteristics of the vertical and horizontal AGV transportation systems that depend on the given design parameters were provided. This approach, however, is described as deterministic parametric and is similar to the one that Chin introduced [7]. Therefore, it is considered that no study has evaluated and analyzed the systems optimally designed to satisfy the various transportation demands.

In this study, as described above, the systems were designed optimally to meet the given demands by using the proposed methodology. After that, the following approaches were used to overcome the second challenge point:

- Comparison of the systems based on the construction cost depending on the optimal design parameters.
- Analysis of the construction costs according to how they are influenced by the design parameters and tendency of the changes in the parameters.

From above two results, each AGV transportation system is relatively evaluated for the various imposed demands, and the important factor for the construction cost of the system and the relevance between each designed parameter are made clear. Finally, the most convenient system for the demands is presented.

## II. TWO DIFFERENT AGV TRANSPORTATION SYSTEMS

### A. The AGV Transportation System

The two typical AGV transportation systems are shown in Fig.1. Fig.1(a) shows the well-known vertical AGV transportation system that has already been introduced into

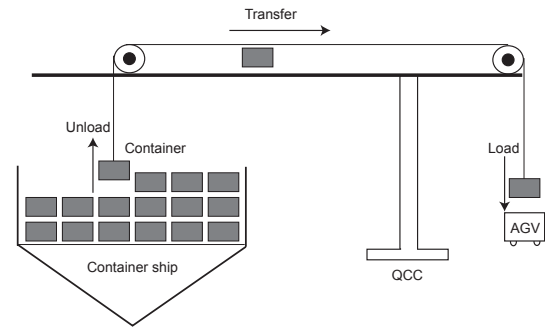


Fig. 2. Loading/Unloading operation by AGVs and QCCs in the quay area (side view)

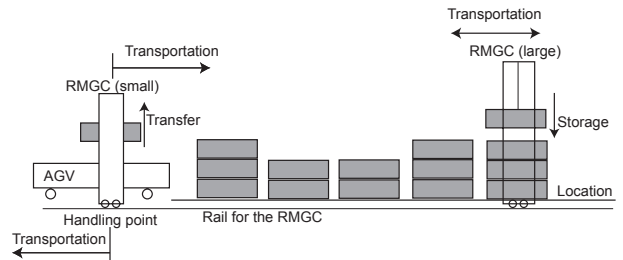


Fig. 3. Transporting/Transferring/Storing operation by AGVs and RMGCs in the container yard area (side view in the vertical system)

the port of Rotterdam as an automated port container terminal. Fig.1(b) shows the horizontal AGV transportation system that has been introduced into some ports as a manned system. These two systems have been used as unmanned and manned systems from the viewpoint of the system manageability with disregard to the system efficiency.

In this study, we first divide the systems into three kinds and four areas, namely, the quay area, two transportation areas, and the container yard area, for optimal design. Here, the location that is shown in Fig.1 represents the

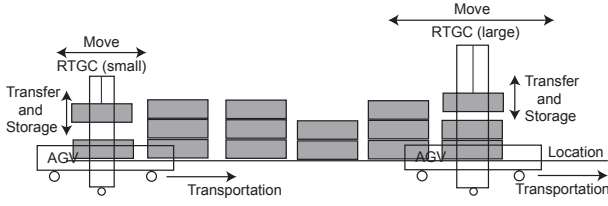


Fig. 4. Transporting/Transferring/Storing operation by AGVs and RTGCs in the container yard area (side view in the horizontal system)

temporal container storage space, whereas the constraint, i.e., the capacity of each container yard area, is equal. The design objects are the number of AGVs, Automated Transfer Cranes (ATCs), and passing paths in the vertical system; on the other hand, the AGVs and ATCs are the design objects in the horizontal system. For an optimal design, we use the following design and evaluation criteria: (a) the traffic intensity, (b) the system throughput, that is, the number of containers transported in a unit of time, and (c) the average number of AGVs at each area.

#### B. Definition of the Agent's Operation in Each Area

Here, let us define the agent's operations in each area as follows:

**Quay area:** A Quay Container Crane (QCC) that is deployed between a container ship and an AGV loads a container to the AGV as shown in Fig.2.

**Container yard area:** An AGV transfers a container to an ATC which works on a location; then, the ATC transports and stores the container into the location as shown in Fig.3 and Fig.4.

**Transportation area:** This area is the AGV transportation route between the quay and container yard area. There are only AGVs and their transport containers.

#### C. The Vertical AGV Transportation System

As shown in Fig.1(a), in the vertical AGV transportation system, the locations are vertically arranged for the container ship. The features of the system are listed as follows: (1) the length of the AGV route does not depend on the number of locations; (2) a container handling point between the AGV and ATC is located in a place; (3) the ATC needs to transport and store the container since the handling point is fixed at one location (see Fig.3). Therefore, an advantage of the system is that the AGV can circulate through a short route.

In the vertical system, a rail wheel ATC, that is, a Rail-Mounted Gantry Crane (RMGC), is used since the RMGC needs to transport with holding the container. In general as well as in this study, since two RMGCs of different sizes work in one location, they can cross each other while transporting and storing the container.

**1) Transportation Procedure in the Vertical System:** The AGVs continue to circulate until they successfully complete all tasks by the following procedure:

**Step1** An AGV loads a container with a QCC in the quay area as shown in Fig.2.

**Step2** The AGV transports the container from the quay area to the assigned location in the container yard area through the transportation area.

**Step3** The AGV goes to a handling point that is adjacent to the assigned location.

**Step4** If an RMGC is already working on the previous task, the AGV needs to wait until it can work on the passing path (see Fig.1(a)).

**Step5** The AGV begins transferring the container to an RMGC (see Fig.3).

**Step6** The AGV that has already transferred the container to the RMGC goes back to a QCC in the quay area through the transportation area.

**Step7** The RMGC to which the container has been transferred transports it to a storage point, stores, and then returns to the handling point again. Back to step 1.

In this study, we define one cycle of the above transportation procedure as the "Task".

#### D. The Horizontal AGV Transportation System

As shown in Fig.1(b), the locations are horizontally arranged for the container ship in the horizontal AGV transportation system. The features of the system are listed in the following: (1) the length of the AGV route depends on the number of locations; (2) a container handling point is anyplace on the route that is adjacent to a storage point; (3) since the AGV can transport a container to the storage point in the location, the ATC does not need to transport but only to transfer and store a container (see Fig.4). Therefore, from feature (2), since the length of the AGV route increases as the number of locations increases, the transportation efficiency and the construction cost must be taken into consideration. As an advantage of the system, it is possible to transfer the container by the multiple AGVs and ATCs at the same time on the same location. However, in that case, there is another transferring AGV in front of the transporting AGV on the same route adjacent to the location. Therefore, since there is no passing path like the vertical system, the AGV needs to stop.

In the horizontal system, a rubber tire-type ATC, i.e., a Rubber Tire Gantry Crane (RTGC), is used. This is because the RTGC is only required to transfer and store the container. In general as well as in this study, two RTGCs of different sizes are working in one location; therefore, they can cross each other while moving and storing containers.

**1) Transportation Procedure in the Horizontal System:** The AGVs continue to circulate by the following procedure:

**Step1** As in the vertical system, an AGV loads a container with a QCC in the quay area, as shown in Fig.2.

**Step2** The AGV transports the container from the quay area to the assigned location in the container yard area through the transportation area.

**Step3** The AGV goes to a handling point that is adjacent to an assigned storage point; it then calls for an

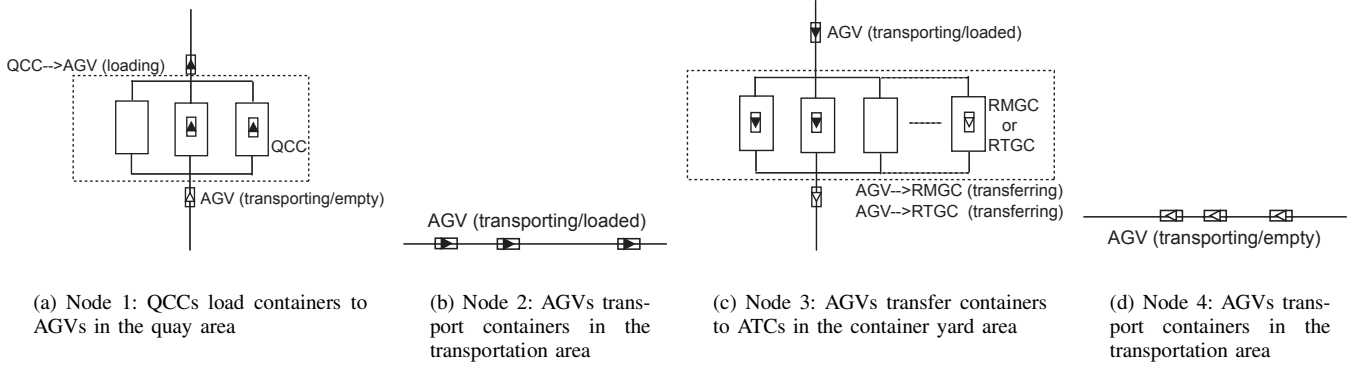


Fig. 5. Definition of an agent's behavior at each node (top view)

RTGC for transferring after arriving at the point and waiting for the work (see Fig.4).

Step4 If there is an idling RTGC on the assigned location, it moves to the handling point; otherwise, the AGV needs to keep calling for an RTGC.

Step5 The AGV begins to transfer the container to an RTGC after the RTGC arrives at the point.

Step6 The AGV that has already transferred the container to the RTGC goes back to a QCC in the quay area through the transportation area.

Step7 The RTGC to which the container has been transferred stores it at the storage point and then waits for the next task from the next AGV. Back to step 1.

### E. Assumption of the AGV Transportation System

As shown in Fig.2, Fig.3, and Fig.4, it is assumed that the time-spans for loading and transferring in the quay and container yard areas are the constants in each transportation system that are shown in Fig.1. Here, the time taken to pass each area by the AVG follows an exponential distribution service time due to the transportation congestions by the AVGs, container transfer between the container ship and QCC, and container transportation and storage by the ATC. However, in this study, we assume a fixed passing time at the quay area for the sake of simplicity. On the other hand, in the transportation and container yard area, we need to consider each passing time in the design process because the times depend on the number of AGVs and ATCs. In addition, the location, where the idling ATC is, becomes the priority destination since a container is assigned based on the First-In First-Out (FIFO) rule. Concerning the number of QCCs, three fixed QCCs are used because the scale of a berth is fixed.

## III. OPTIMAL DESIGN FOR THE TRANSPORTATION DEMAND

### A. Modeling the Transportation System

As a result of the modeling of the AGV transportation systems shown in Fig.1 by using the closed-cyclic queuing network model of the queuing network theory [9] [10], the systems can be represented by nodes, as shown in Fig.6. In the modeling, the divided four areas in Fig.1 are assigned

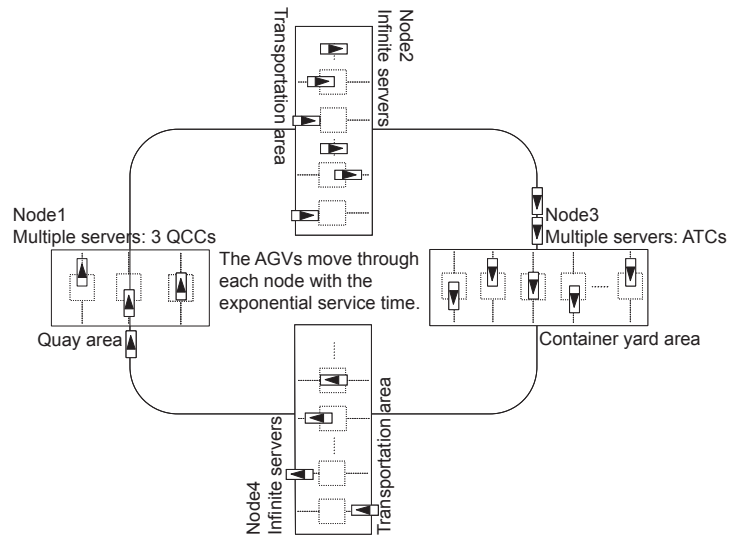


Fig. 6. Modeling the transportation system

from nodes 1 to 4 (see Fig.5). Here, concerning the time needed to pass each node, we defined these time costs as follows: the time taken to pass node 1 is equivalent to the time taken for the second AGV to leave the QCC after the front AGV has left the QCC (Fig.5(a)); the time taken to pass nodes 2 and 4 is equivalent to the transporting time between nodes 1 and 3 (Fig.5(b); Fig.5(d)), and the time taken to pass node 3 is equivalent to the time taken by the AGV upon arriving at the handling point until the AGV finishes transferring the container to the ATC (Fig.5(c)). In the quay area, i.e., node 1, the AGVs are serviced by the QCCs, and, in the container yard area, i.e., node 3, the AGVs are serviced by the RMGCs and RTGCs in the vertical and horizontal systems, respectively. Therefore, these two nodes consist of multiple servers, where the number of each server is equivalent to the number of QCCs and RMGCs or RTGCs. On the other hand, in the transportation area, i.e., nodes 2 and 4, there are only transporting AGVs. Therefore, these two nodes consist of infinite servers. The AGVs circulate through those nodes in the network until their transportation tasks are completed.

TABLE I  
SPECIFICATION OF AGV, RMGC, AND RTGC

		AGV (Loaded) / (Empty)	RMGC (Loaded) / (Empty)	RTGC (Loaded) / (Empty)
Maximum traveling velocity	[m/s]	5.56 / 6.94	2.0 / 2.5	- / 2.5
Maximum cornering velocity	[m/s]	1.39 / 1.39	- / -	- / -
Acceleration	[m/s <sup>2</sup> ]	0.15 / 0.15	0.1 / 0.1	- / 0.1
Deceleration	[m/s <sup>2</sup> ]	0.63 / 0.63	0.4 / 0.4	- / 0.4

### B. Agent's Specification and Time Cost at Each Node

Table I shows the specifications for the AGV, RMGC, and RTGC [11]. Each specification is shown as (loaded)/(empty). Due to the fact that the RMGC and RTGC are driven directly and the RTGC does not transport the container, their specifications are shown as (-) in Table I. Each time cost can be derived from the transportation simulator that implements the transportation layout and the actual agent's specifications, as shown in Fig.1 and Table I. In this simulator, from the assumption of this study, the loading and transferring times in the quay and container yard area by the agents are given as 60[s] and 30[s], respectively. These are inputted parameters into the task-flow analyzer shown in Fig.7.

### C. Formulation of the Transportation System

As a result of the modeling shown in Fig.6, the transportation systems and the behavior of AGVs in the systems can be formulated based on the following queuing network theory. It is possible to design each transportation system based on the following design criteria. Here, the number of nodes, the service time at each node, the number of servers in the nodes, the traffic parameter, and the number of relative arrivals of AGVs at the node are inputted parameters. Eq.(1) is the traffic intensity at each node, and we can analyze the bottleneck node numerically by this equation. Eq.(2) is the throughput at each node, and, using this equation, we can determine whether or not the system satisfies the transportation demands. The optimal number of AGVs and ATCs are derived on the basis of Eq.(2) and the hybrid design algorithm proposed in [6]. Eq.(3) and Eq.(4) are the average number of AGVs at each node, and we can design the needed number of passing paths by using these equations in the vertical system. Eq.(3) is used for infinite servers, and Eq.(4) is used for multiple servers.

$$\alpha_{j1}(K) = \rho_{j1} \frac{G(K-1)}{G(K)} \quad (1)$$

$$\tau_{j1}(K) = h_{j1} \frac{G(K-1)}{G(K)} \quad (2)$$

$$\phi_{j1}(K) = h_{j1} \frac{G(K-1)}{G(K)} \quad (3)$$

$$\phi_{j1}(K) = \frac{1}{G(K)} \sum_{0 \leq x_j \leq K} x_j q_j(x_j) G_{[j]}(K-x_j) \quad (4)$$

where

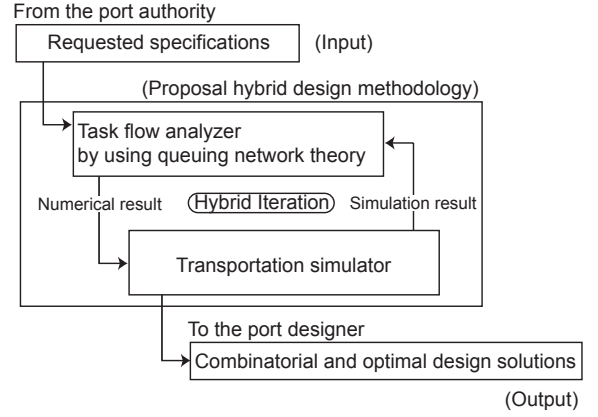


Fig. 7. Proposed hybrid design process

$K$ : Number of AGVs

$\rho_{j1}$ : Traffic parameter

$h_{j1}$ : Number of relative arrivals of AGVs

$N$ : Number of nodes

$x_j$ : Number of AGVs around the node  $j$

$q_j(x_j)$ : Convolution parameter

$G(K)$ : Normalization constant

$G_{[j]}(K)$ : Normalization constant of  $j$ -complement,

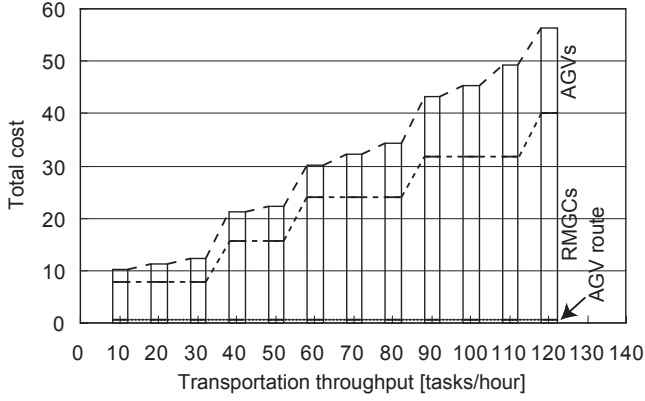
where the  $\rho_{j1}$  is given by {the number of relative arrivals of AGVs at a node  $j$ }  $\times$  {the service time, i.e., the time cost at a node  $j$ }.  $h_j$  is given by {the number of total task} = {at each node  $j$ } because each system is modeled by the cyclic single queuing network. These parameters can be obtained with the initial system specifications. The function  $G(K)$  is defined so that all the probabilities:  $P(x_1, x_2, \dots, x_N)$  add up to one. The  $j$ -complement network is equal to the normalization constant ( $G(K)$ ) given by removing the  $j$ th node in the queuing network, that is,  $G(K)$  and  $G_{[j]}(K)$  are obtained by the following convolution operations (Eq.(5), Eq.(6)):

$$G(K) = \sum_{x_1+x_2+\dots+x_N=K} \prod_{j=1}^N q_j(x_j) \quad (5)$$

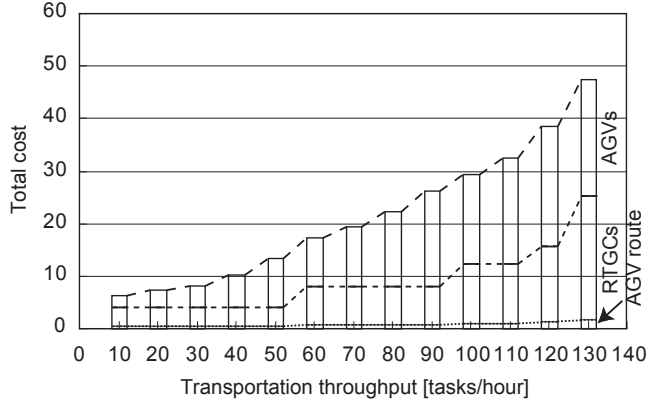
$$G_{[j]}(K) = \sum_{x_1+\dots+x_{j-1}+x_{j+1}+\dots+x_N=K} \prod_{i=1, i \neq j}^N q_i(x_i) \quad (6)$$

The detailed operation algorithm of Eq.(5) and Eq.(6) is described in [6] [10].





(a) Total cost and ratio of the vertical transportation system



(b) Total cost and ratio of the horizontal transportation system

Fig. 8. Total construction cost and ratio of the design parameter of each AGV transportation system

#### D. Design Process and Parameters

Fig.7 shows the proposed hybrid design process from the demand to the design solutions, which includes the numerical theory and simulation-based optimization method. From the inputted requirement, initial parameters are inputted into the proposed hybrid design methodology. In this methodology, the design parameters that are derived by the task-flow analyzer using the queuing network theory (from Eq.(1) to Eq.(4)) are inputted into the transportation simulator. These two approaches represent hybrid iterations; the final combinatorial optimal design solutions are derived if the output results are in agreement. The detailed design algorithm is described in [6].

The design parameters of the vertical and horizontal AGV transportation systems are described as follows:

- The vertical AGV transportation system
  - Number of AGVs
  - Number of RMGCs
  - Number of passing paths
- The horizontal AGV transportation system
  - Number of AGVs
  - Number of RTGCs

### IV. EVALUATION AND ANALYSIS

#### A. Evaluation Criteria

In these design experiments, we gave the requirement specification for the system as the constraint for the optimal design, in which the constraint indicates the system throughput, that is, the number of containers that is transported within one hour. The number of total transportation tasks or containers is 600. In these design conditions, the required throughput, that is, the various transportation demands, is given as follows: 10, 20, 30, ...; then, the design solutions for each demand are derived. For the derived solutions, the total construction cost of the vertical and horizontal systems ( $TC_v$  and  $TC_h$ ) is derived by Eq.(7) and Eq.(8). These systems are constructed by considering

the following parameters with the given evaluation factors,  $a$ ,  $b$ ,  $c$ , and  $d$ .

- Number of AGVs
- Number of ATCs (i.e., RMGCs and RTGCs)
- Total length of the AGV transportation route
- Total cost of the vertical AGV transportation system
$$TC_v = a \times AGVs + b \times RMGCs + d \times route \quad (7)$$
- Total cost of the horizontal AGV transportation system
$$TC_h = a \times AGVs + c \times RTGCs + d \times route \quad (8)$$

With considering the actual ratio of construction costs, that is, the agent inputting cost ( $[cost/agent]$ ) and setting up the cost of the magnetic tape for the AGV ( $[cost/m]$ ), these factors are given as follows:  $a = 1$ ,  $b = 4$ ,  $c = 2$ ,  $d = 1.5 \times 10^{-4}$ .

#### B. Comparison and Evaluation Results

Fig.8 shows the comparison of the results of the total construction cost. A ratio of design parameters that influences the construction cost is shown by dotted lines in Fig.8. From this result, it is noticeable that the horizontal system can construct a more efficient transportation system than the vertical system for all the demands because the total cost is less than that of the vertical system. This result is attributed to the fact that the AGV is mainly used in a horizontal transportation system; in addition, the AGV has the following advantages as the transportation agent: 1) it has a high transportation performance, and 2) it can be implemented at a lower cost than the RMGC and RTGC. Only the horizontal system can satisfy the demand for the required throughput of 130 containers. This result is attributed to the fact that the shortest AGV route, i.e., the advantage of the vertical system, is saturated with the AGVs. With a throughput in excess of 140 containers, the design solutions were not achieved because of the occurrence of bottlenecks.

Considering the influence on the construction cost, the AGV route is negligible; however, concerning the agents,

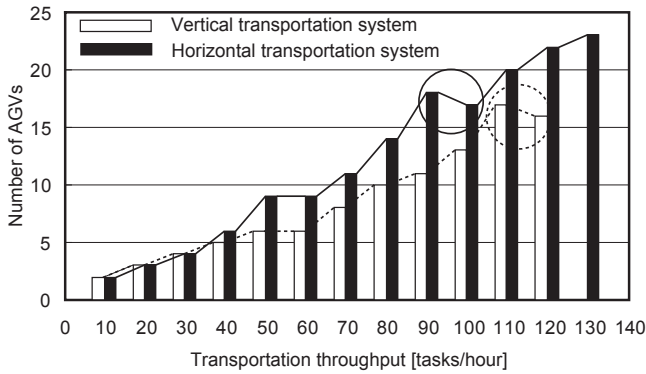


Fig. 9. Tendency of design solutions of the number of AGVs

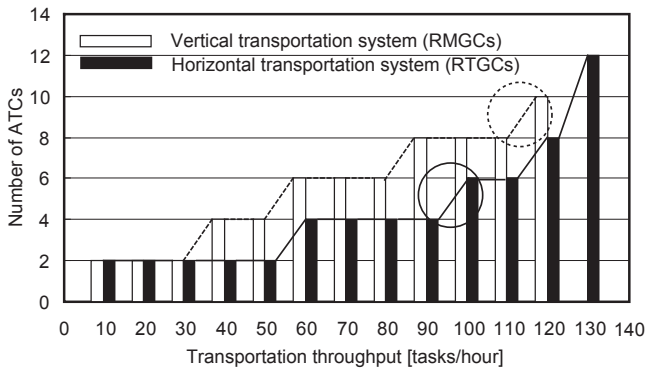


Fig. 10. Tendency of design solutions of the number of ATCs

the RMGC has the largest impact on the agents. Therefore, although the RMGC can transport the container in the container yard area, the number of inputted RMGCs influences the construction cost of the system because it is a high-cost agent.

### C. Analysis of the Designed Parameters

The optimal numbers of AGVs, RMGCs, and RTGCs derived for each transportation demand in the vertical and horizontal AGV transportation systems are shown in Fig.9 and Fig.10. From Fig.9, which shows the demand of a low throughput, the difference in the number of inputted AGVs in each system was negligible. However, the increase in the number AGVs in the horizontal system is noticeable as the required throughput increases. The reason for this tendency is that the AGV is used more in the horizontal system than in the vertical system. For instance, although the AGV just goes to the handling point and cannot go to the storage point in the vertical system, the AGV can go to the storage point in the horizontal system. On the other hand, as a result of the number of ATCs, from Fig.10, the number of RMGCs in the vertical system is higher than the number of RTGCs in the horizontal system. The reason of this result is that a plenty number of RMGCs are needed than the number of RTGCs because the RMGC also needs to transport the container, that is, the RMGC is also mainly used as the AGV in the vertical system.

Regarding the changes in the number of agents, the decrease in the number of AGVs is noticeable at the point of throughputs from 90 to 100 and from 110 to 120 in each transportation system, as shown in Fig.9. This result is led by changes in the number of ATCs for each demand, as shown in Fig.10. Therefore, there might be a case in which adding more ATCs sometimes leads to a decrease in AGVs. With regard to the changes in the length of the AGV route, the influence on the construction cost is negligible because the increase in the length, which depends on the number of the locations, is 414[m] for each additional location and is equal to 0.7 points of the total cost (see Fig.8). Therefore, the influence of the increase in the length of the AGV route is also negligible compared to the total cost and transportation efficiency.

In this design and evaluation experiment, by using as many AGVs as possible for transportation and ATCs for storage of the containers, the effectiveness of port operations can be increased. Therefore, the horizontal AGV transportation system is highly effective in these transportation demands.

## V. CONCLUSION

In this paper, we optimally designed actual AGV transportation systems using the proposed hybrid design methodology. We then compared the systems based on the total cost of construction; then, the validity of each transportation system for the given demand was presented. As a result, it was proven that the horizontal AGV transportation system is a more convenient system than the vertical AGV transportation system for all demands.

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