Comparison of an AGV Transportation System by Using the Queuing Network Theory

Satoshi HOSHINO and Jun OTA
Dept. of Precision Engineering, School of Engineering
The University of Tokyo
Bunkyo-ku, Tokyo 113-8656, JAPAN
E-mail: {hosino, ota}@prince.pe.u-tokyo.ac.jp

Akiko SHINOZAKI and Hideki HASHIMOTO
Mitsubishi Heavy Industries, LTD.
Sagamihara-shi, Kanagawa 229-1193, Japan

Abstract— **In this paper, we provide the comparison indicator of the AGV transportation systems. For this purpose, we propose an optimal design methodology for the AGV transportation system by using the queuing network theory. In this methodology, the queuing network theory and a simulation-based optimization method are integrated to obtain the optimal design parameters (i.e., these are the design solutions of this design problem). In this study, two different types of the AGV transportation systems are designed. Then the performance of transportation is compared. Finally, the characteristics of each transportation system that depends on the design parameters is provided.**

I. INTRODUCTION

Recently, an AGV (Automated Guided Vehicle) transportation system can be considered that it is useful to be implemented for the automation in a port container terminal. As an actual AGV transportation system, there are different two types of systems. These two types of transportation systems are named vertical and horizontal transportation systems in this paper. Before beginning a design of the port container terminal, the system type should be selected in accordance with the intended use of the port authorities. However it is difficult to select the more useful system as the case may be, because no study has compared these systems based on the evaluation of the system. Therefore, it is necessary to provide the comparison indicators for the port authorities. For this issue, in this paper, we propose an optimal design methodology for a transportation system with AGVs; then, evaluate and compare the two different types of systems based on each of their performances.

Conventional research relating to the design of transportation systems is generally divided into two categories: (1) An optimal design method by using only a numerical modeling of the system [1] [2], and (2) An optimal design method based on solving problems with a simulation, i.e., this is named a simulation-based optimization method [3]. As a former method, Abe *et al.* [1] [2] have proposed a design method using the open queuing network of the queuing theory for the optimal system design. As a latter method, Chiba *et al.* [3] have proposed an integrated design methodology in AGV transportation systems. In this study, by solving an iterative direct problem using the genetic algorithm (GA), the method calculates suitable flow path for various transporter routing of AGVs, and obtain the set of transporter routing, the number of AGVs, and flow paths. However, because this system is the large-scale transportation system, the following problems arise when only each either method is used.

- It is impossible to analyze a gap between the numerical model and an actual system.
- It is needed a significant amount of operation time to search whole design parameters.

To achieve the optimal design, we applied a closed queuing network of the queuing network theory for the transportation systems for modeling. For the above problems, we aim to integrate the queuing network theory into the simulation-based optimization method and iterate the design process. Therefore, our proposal methodology has the following effects:

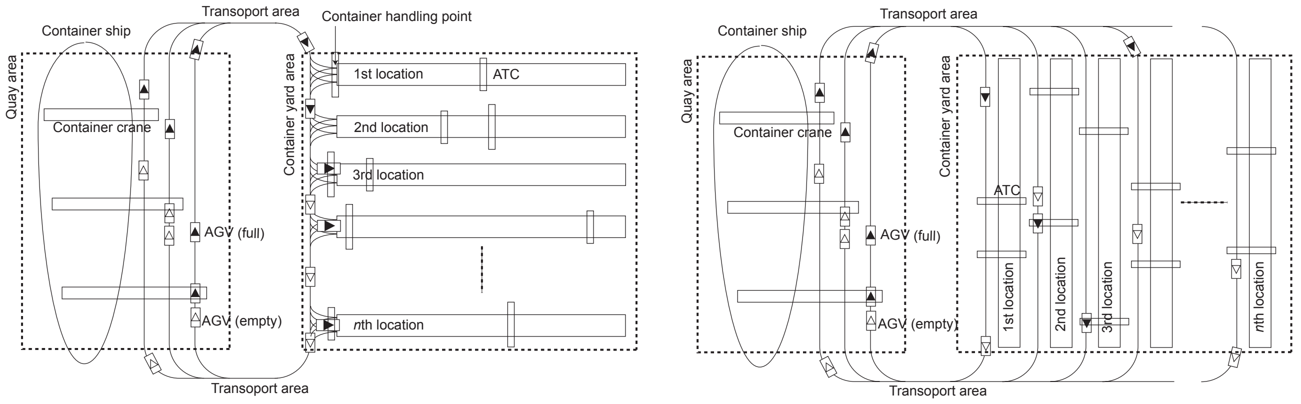
1. It is possible to model, design, and analyze the transportation system which includes the gap between the numerical model and the actual system.
2. The operational time deriving the design solutions is less than that required in the simulation-based optimization method.
3. It is possible to evaluate and compare the system proposed here.

Moreover, as we described above, it is necessary to clarify the characteristics of transportation systems by the comparison of the different types of the systems. Ioannou *et al.* and Liu *et al.* considered the design based on a simulation and evaluation of several Automated Container Terminals (ACTs) [4] [5]. They then proposed a method for designing and comparing the characteristics of the ACT that are necessary for meeting the projected demand. However, it is impossible to select the system based on the performance of transportation because their proposed methodology depends on the design costs. In the conventional research relating to the comparison of the transportation system, no studies have compared with the different types of the AGV transportation systems based on the transportation efficiency. Therefore, in this paper, we quantitatively compare and evaluate the characteristics of the AGV transportation systems.

II. THE AGV TRANSPORTATION SYSTEM IN A PORT CONTAINER TERMINAL

A. The AGV Transportation System

In this paper, two types of the AGV transportation systems are designed. In this study, each AGV transportation system is divided into three areas, namely, the quay, transport, and container yard areas as shown in Fig.1. In this system, the AGVs continue to circulate until they successfully complete all tasks by the following procedure:



(a) Vertical transportation system

(b) Horizontal transportation system

Fig. 1. Two Types of the AGV Transportation Systems

step1 The container cranes working in the quay area load a container on the AGVs from the container ship.

step2 A location is assigned to the AGV as the destination in the container yard area at the time when the AGV leaves the quay area.

step3 The AGV goes to the container yard area through the transport area.

step4 The AGV arrives at the assigned location. If it encounters another AGV in its front, this AGV has to wait until the front AGV finishes transferring the container to an ATC (Automated Transfer Crane); then, this AGV goes to a handling point or starts to transfer a container.

step5 If the ATC is already at the handling point, the AGV will transfer the container to the ATC. Otherwise, if the ATC is already engaged, the AGV will wait at this point.

step6 The ATC stores the container.

step7 The AGV that has already transferred the container goes back to the quay area. (back to step1)

where, the task has following informations: position of the container crane, position of the location, and the storing point in the location. In this system, two ATCs that are different size work at the same location. The location means the container yard space. Therefore, they can cross each other when they store the container.

B. Vertical Transportation System

Fig.1(a) shows a vertical transportation system. In this system, the locations are verticality arranged for the container ship. The AGV goes to which handling point in the container yard area; then, transfers the container. The transferred container is transported and stored by the ATC. In the step4, if another AGV is already working in front of this AGV, this AGV goes to the passing path; then, this path will be working path after the front AGV finishes transferring. Therefore, in case of this system, the ATC transfers, transports, and stores the container. The feature of this system is that the length of the AGV's route does not depend on the number of locations. Namely, it is expected that the AGVs run efficiently in case of the small number of AGVs in this system.

C. Horizontal Transportation System

Fig.1(b) shows a horizontal transportation system. In this system, the locations are horizontally arranged for the container ship. The AGV goes to the location side in the container yard area; then, the ATC transfers the container from the AGV at the yard point. The ATC just stores the container to the yard point; then, goes to the next yard point. Therefore, in case of this system, the ATC transfers and stores the container. The feature of this system is that the length of the AGV's route depends on the number of the locations. Therefore, it is expected that the AGVs run efficiently in case of the large number of AGVs in this system.

D. The Combinatorial Optimization Problem

The parameters of the design object in this study are described in the following:

- Number of AGVs
- Number of ATCs
- Number of passing paths (i.e., this is the buffer)

where, the number of passing paths is designed to avoid the traffic congestion only in case of the vertical transportation system. All containers should be successfully transported from the container ship to the container yard area within a limited amount of time. In this constraint, the minimum number of agents with which the requirement is satisfied is used as a performance function.

E. Assumption of the AGV Transportation System

Each location of this system becomes the destination of a container with a certain probability for the sake of simplicity. As the assignments are made, any location without an engaged ATC becomes the priority destination. Additionally, the general working time of each container crane depends on the position allocated to each container in the container ship. However, we provide a fixed working time for the sake of simplicity. Moreover, three fixed container cranes are used because the scale of a berth is fixed.

III. QUEUING NETWORK THEORY

A. Cyclic queuing network

In the closed queuing network, the number of agents is constant since agents can neither arrive nor leave the

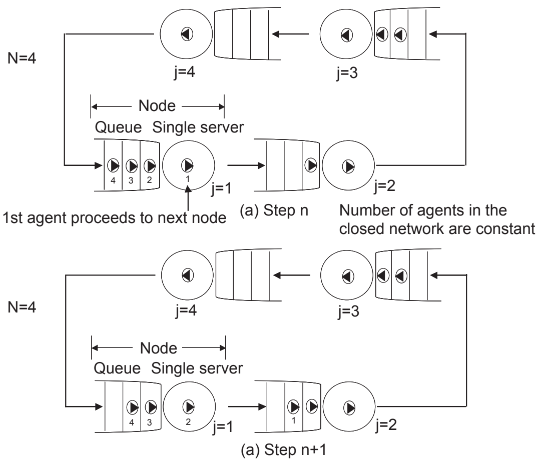


Fig. 2. A State Transition Diagram in the Cyclic Queuing Network Composed by a Single Server

system, but, rather, circulate repeatedly through the various nodes at all times [6]. Thus, a closed queuing network, which includes N queues in tandem, i.e., a series of N queues arranged cyclically in such a way that agents proceed sequentially through the cycle, returning to the first node after being serviced at node N, is called a cyclic queuing network [7]. In this study, the cyclic queuing network is applied to the transportation system for modeling. Fig.2 indicates the state of transition in the system from step n (Fig.2a) to step $n+1$ (Fig.2b). Fig.2(a) and (b) show that only the first agent proceeds to the next node; then, the next queuing agent (the second agent in that queue) goes into the single server, and the third and fourth agents proceed forward in the queue.

B. Performance evaluation method

Ottjes *et al.* and Duinkerken *et al.* use some performance indicators when they design the ACTs by a specific transport simulator [8] [9]. In this paper, working AGVs in the system are defined as network agents. 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 into the queuing network theory. After that, (a) traffic intensity (Eq.1), (b) throughput (Eq.2), and (c) the average number of AGVs at the node (Eq.3, 4) are obtained. The following are the performance evaluation criteria: (a) is used to locate bottlenecks in the system, (b) is used to determine whether or not the system satisfies the requirement, and (c) is used to design the number of buffers in case of the vertical transportation system.

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

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

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

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

where,
K: Number of AGVs
ρ_{j1}: The 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 in the network

where the ρ_{j1} is given by $\{$the number of relative arrivals of AGVs at a certain node $j\}$ $\times$ $\{$the service time at a certain node $j\}$ and h_j is the number of relative arrivals of AGVs at node j. In this study, the number of relative arrivals of AGVs is the same for each node because the design object is modeled by the cyclic queuing network (Fig.2). Therefore, the number of tasks is equal to the number of relative arrivals of AGVs. These parameters can be obtained with the system specifications. The function $G(K)$ is defined so that all the $P(x_1, x_2, ..., x_N)$ add up to one. The j-complement network is equal to the normalization constant ($G(K)$) given by removing the jth node in the closed queuing network, that is, $G(K)$ and $G_{[j]}(K)$ are obtained by the convolution operation (Eq.5, 6) described in following [6]:

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

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

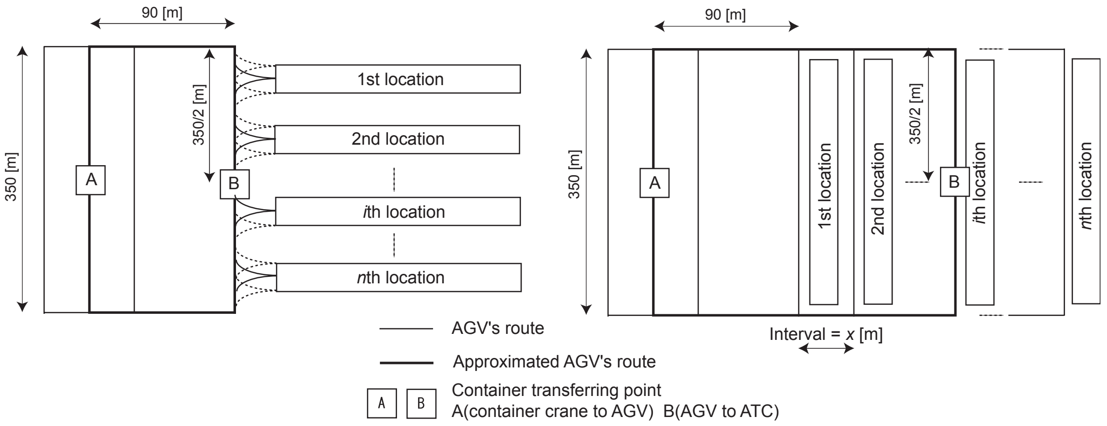
C. Modeling of the Transportation System

Fig.1 is modeled as shown in Fig.3 based on the cyclic queuing network. The three areas in Fig.1 are assigned from nodes 1 to 4, and the number of cranes and ATCs in the quay area and container yard area are the number of servers at nodes 1 and 3. AGVs circulate through those nodes in the network until their transport tasks are completed.

IV. SYNTHETICAL DESIGN FOR THE AGV TRANSPORTATION SYSTEM

A. Transport specifications of the AGV and ATC

TableI indicates the specifications for the AGV and ATC. Fig.4 shows the transport routing for the AGVs. It is assumed that the AGVs go through the heavy black lines in each transportation system for the sake of simplicity. Thus, in cases in which there is no traffic congestion, the time at node2 (A to B) and node4 (B to A) is calculated: 165 [s] and 122 [s] (Fig.4a), $\{440 + x \times (n-1)/2\}/2.57$ [s] and $\{440 + x \times (n-1)/2\}/3.48$ [s] (Fig.4b), respectively. where, x is an interval of the path in the container yard area. The interval is 32 [m] in this design. 2.57 and 3.48 are the average speed of the AGV [m/s], respectively. On



(a) An approximated AGV's route in the vertical system (b) An approximated AGV's route in the horizontal system

Fig. 4. Modeling of Each Transport Routing

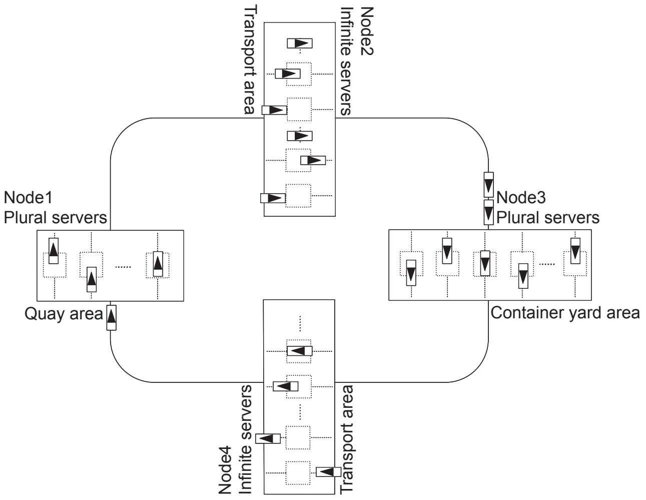


Fig. 3. Modeling the Transportation System

the other hand, the loading/unloading and transferring time of the container crane and ATC are fixed because of the assumption; therefore, in this study, the time costs of nodes 1 and 3 are given as 60 [s] and 30 [s], respectively. These are the initial input parameters to the queuing network theory. However, if the ATC is not at the handling point when the AGV arrives, the AGV will need to wait at this point.

TABLE I
SPECIFICATION OF AGV AND ATC

	AGV (full)	AGV (empty)	ATC (full)	ATC (empty)
Max. speed [m/s]	5.56	6.94	2.25	2.0
Cornering [m/s]	1.39	1.39		
Acceleration [m/s^2]	0.15	0.15	0.1	0.1
Deceleration [m/s^2]	0.63	0.63	0.4	0.4

B. The Proposed Design Algorithm

Fig.5 indicates the proposed design architecture. In our design approach, the input parameter is a requested specification such a transport time for the transportation system. For this input parameter, the design solutions are derived by our proposed design methodology.

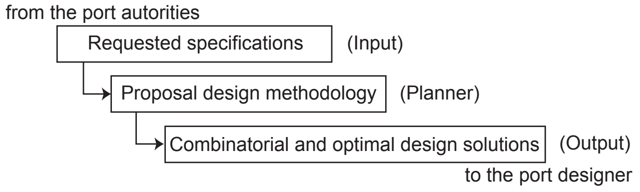


Fig. 5. Systhetical Design Architecture

Fig.6 indicates the design algorithm that we propose. In this design algorithm, a transportation simulator is used to (1) simulate a designed system, and (2) calculate the transport delay by the AGV friction.

The time cost at each node and the number of container cranes and ATCs are inputted as initial parameters. After that, the throughput is obtained. The throughput is evaluated based on certain requirements. If the throughput satisfies the requirements, the minimum number of AGVs is derived as the optimal number of AGVs. However, if it does not satisfy the requirements, the number of ATCs is increased by two, and the design process is then iterated. In this study, the number of AGVs is designed not to exceed 30 in order to avoid adding the AGVs recklessly.

The transport simulator then operates based on the derived number of AGVs to evaluate whether or not this theoretical result also satisfies the requirements. If the simulation result also satisfies the requirements, the combinatorial design solutions are obtained, as well as a design process in which the number of ATCs is changed and the process is iterated. Otherwise, the time at nodes 2, 3, and 4 is calculated by the simulator, and then the calculated time can be used as an input parameter.

This design process will be iterated until the derived number of AGVs in step n is not lower than the derived number of AGVs in step $n-1$.

C. The Requirement setting

In this study, one of the constraints is the time of berthing at a port container terminal; this time is equal to the time

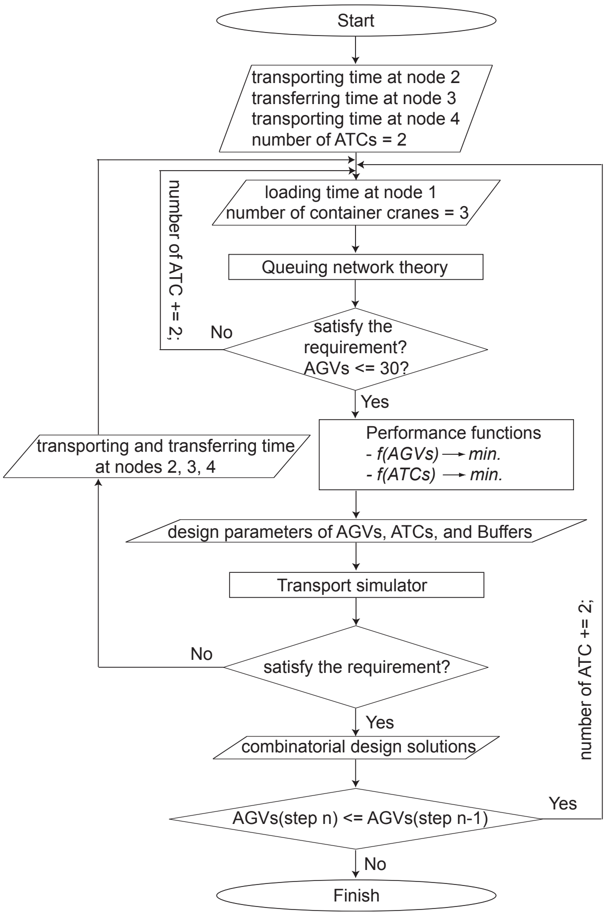


Fig. 6. Design Algorithm by Using the Queuing Network Theory

required to complete the transport. This is, {Transporting Requirement} $\leq$ {System Throughput}. In this design process, the number of transport tasks is 600, and the required transport throughput is 120, i.e., the system has to successfully complete all tasks within 5 hours.

D. The Combinatorial Design Solutions

TableII indicates the number of AGVs at each node in the case of the design solutions are obtained. This result is used for the design of the vertical system. The average number of AGVs at node3 is less than the number of the locations (6 and 7). Therefore, the number of buffers is designed as “0”.

TABLE II
THE AVERAGE NUMBER OF AGVS AT EACH NODE IN THE VERTICAL TRANSPORTATION SYSTEM

Case	Node1	Node2	Node3	Node4
a	6	4	3 < Location:6	4
b	5	4	3 < Location:7	4

TableIII indicates each combination of the optimal design solutions and the time costs at each node in the each type of system (case a, b, and a’). The increase in the time is noticeable as the number of AGVs increases. From this point of view, the relation between the transportation efficiency that depends on the number of AGVs and the time cost needed by the node is the trade-off. Therefore, there are cases in which increasing the number of AGVs worsens the transport efficiency.

Furthermore, since this design result, the horizontal system can achieve transport by the small number of AGVs and ATCs in case of this requirement.

TABLE III
THE COMBINATION OF DESIGN PARAMETERS AND TIME COSTS AT EACH NODE

Type	Case	ATC	AGV	Buffer	Transporting time Node2, 3, 4 [s]
Vertical	a	12	17	0	178, 45, 144
Vertical	b	14	16	0	170, 36, 140
Horizontal	a’	12	15	-	184, 36, 156

E. System Performance Evaluation

The traffic intensity at nodes 1 and 3 are evaluated in each design solutions. As shown in TableIV, in the system which is designed by the derived solution, it can be located that the bottleneck is in the quay side.

TABLE IV
TRAFFIC INTENSITY AT NODES 1 AND 3

Type	Case	Node1 [%]	Node3 [%]
Vertical	a	92.4	44.5
Vertical	b	91.9	33.7
Horizontal	a’	84.6	8.7

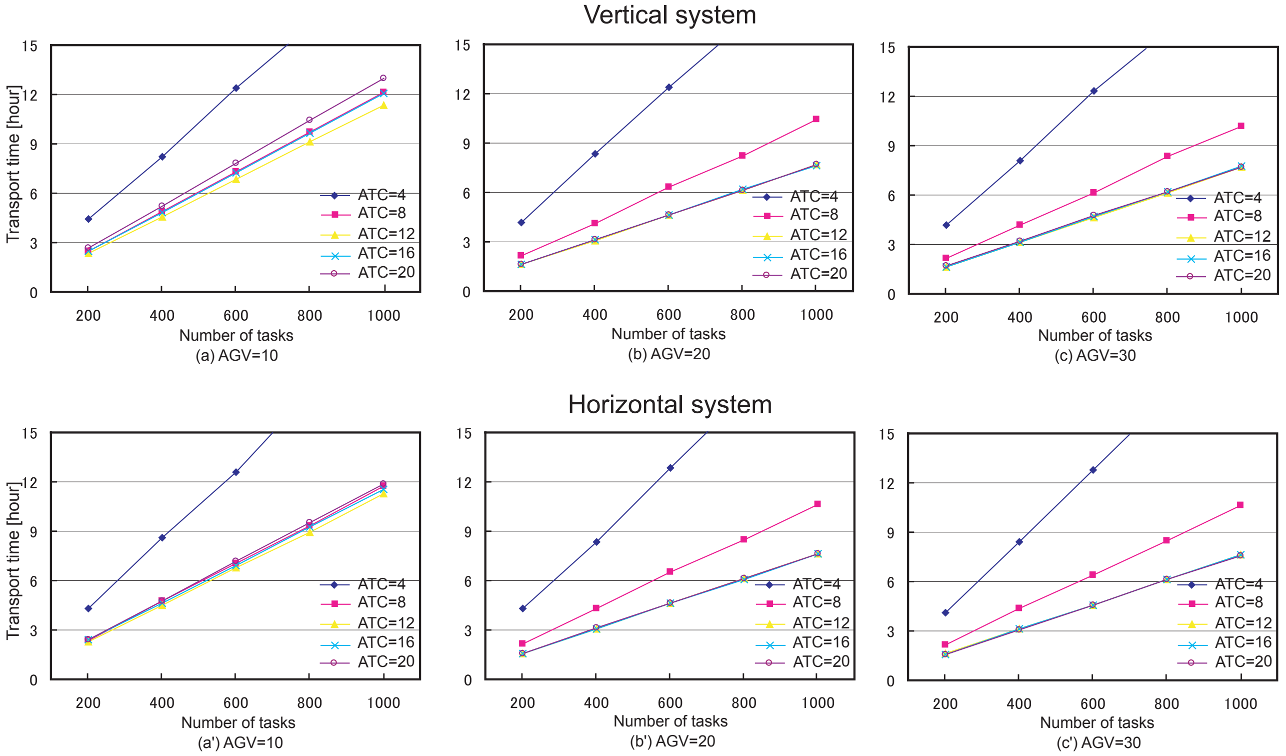
Since these results, it has been confirmed that the traffic intensity of node 1 approximates 100 [%] faster than that of node 3. This shows that more container cranes are needed to obtain much more throughput.

V. EVALUATION AND COMPARISON OF THE TWO TRANSPORTATION SYSTEM

A. Transportation Result

Fig.7 indicates the transportation results in each type of the system. In this simulation experiments, the parameters are given as follows: the number of tasks are 200, 400, 600, 800, 1000, and the number of AGVs are 10, 20, 30, and the number of ATCs are 4, 8, 12, 16, 20. These results prove that the vertical transportation system is useful in case of the small number of AGVs and ATCs (Fig.7a, a’) because the bottleneck occurs in the container yard area, while, the horizontal transportation system is useful in case of the large number of AGVs and ATCs (Fig.7b, b’, c, c’) because the bottleneck occurs in the quay area.

From these results, it is clear that adding more ATCs is effective for the system if the bottleneck is located somewhere in the system. However, it is clear that adding AGVs recklessly is often ineffective for the system because it causes traffic congestion of AGVs in the system. This congestion generally has a bad influence on the transportation system.



(a) AGV=10 (b) AGV=20 (c) AGV=30

(a') AGV=10 (b') AGV=20 (c') AGV=30

Fig. 7. Comparison of the AGV Transportation System

B. Comparison of the Characteristics of the Systems

Here, the characteristics of each type of system are described quantitatively. We then decide which transportation system is more useful when the design parameters are given. Before the bottleneck occurs in the quay area, namely in case of the bottleneck is occurring in the container yard area, we conclude the following:

- In the case where the number of AGVs is less than 10, and the number of ATCs is less than 4 → Vertical system
- In the case where the number of AGVs is more than 10, and the number of ATCs is less than 4 → Horizontal system

On the other hand, in the case of adding a large number of ATCs, where the bottleneck occurs in the quay area, it can be proved that:

- In the case of the number of AGVs is less than 20, and the number of ATCs is less than 8 → Vertical system
- In the case of the number of AGVs is more than 20, and the number of ATCs is more than 8 → Horizontal system

This index is the useful comparison indicator for the port authorities to select the type of the transportation system when the requested specification is provided. Once the type of the system is selected, it is possible to design using our proposed methodology.

VI. CONCLUSION

In this paper, we provided the comparison indicator for the AGV transportation system. For this purpose, we proposed the optimal design methodology for the AGV transportation system by using the queuing network theory. Then, each transportation system was evaluated and compared based on their performances in simulation. Finally, the characteristics of each transportation system were provided.

As future work, it would be necessary to consider the behavioral design of the AGV and ATC and task assignment scheduling problem to improve the efficiency of actual transportation systems.

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