Optimal Design Methodology for an AGV Transportation System by Using the Queuing Network Theory

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Abstract. In this paper, we propose an optimal design methodology for an AGV transportation system by using the queuing network theory. In this study, we deal with an actual transportation system as a combinatorial optimization problem. Therefore, some kind of paths and working multi-agents, such as Automated Guided Vehicles (AGVs), Automated Transfer Cranes (ATCs), and container cranes, are included in this system as design objects. We describe how to derive these design parameters (i.e., design solutions) by the performance evaluation of an AGV transportation system.

1 Introduction

In an automated port transportation system, timeliness is always an important constraint. Therefore, this system offers improvements in efficiency. In this paper, we propose an optimal design methodology for a transportation system with AGVs. This design problem can be considered as combinatorial optimization problem. Therefore, it is necessary to consider the following design elements: (1) an optimal number of working agents to satisfy the requirement, and (2) an optimal number of paths between agents.

Conventional researches relating to the design of transportation systems are generally divided into two categories: (1) A method based on the analysis of the local aspects of the transportation system [1][2], and (2) A method based on solving problems with simulation [3][4]. Abe *et al.* [1][2] proposed a design method using the open queuing network for optimal system design. In this method, a belt conveyor was used at a coaling wharf. However, a transportation system using a transport agent, such as a belt conveyor, which may move constantly, is inadequate for a multi-agent transportation system that includes AGVs. On the other hand, Chiba *et al.* [3] proposed an integrated design methodology in AGV transportation systems. In this study, they designed an optimal number of AGVs and transport routes based on a simulation. Liu *et al.* [4] developed a microscopic simulation model for the purpose of designing, analyzing, and evaluating some different Automated Container Terminals (ATCs).However, these two design methodologies are called simulation-based optimization; therefore, they sometimes need a significant amount of computational time to achieve an optimal design.

For this study, an AGV transportation system shown in Fig.1 was designed. An objective of this study is to establish a specific methodology with the following effects:

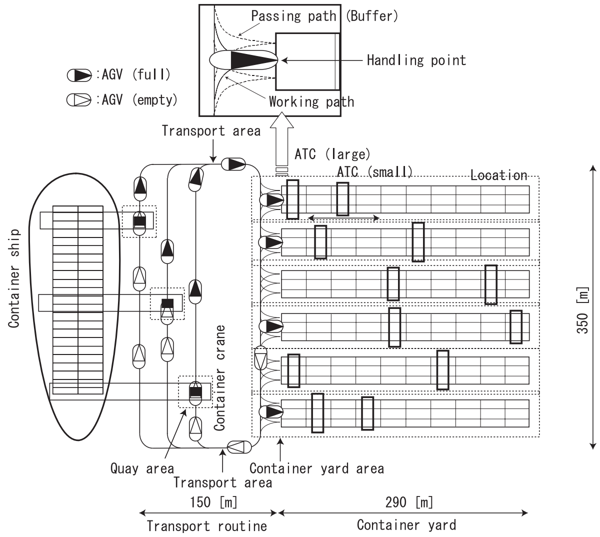

Fig. 1. Vertical layout of AGV transportation system

1. It is possible to model and design the transportation system as a multi-agent system, globally and optimally.
2. The computational time deriving the design solutions is less than that required in the simulation-based optimization method.
3. It is possible to evaluate and analyze the system proposed here.

To achieve the effects outlined above, we applied a closed queuing network, which is used to analyze and design large-scale computer systems for transportation systems. However, because the transportation time changes when the number of AGVs in the system changes, the following problem arises when only the queuing network theory is used.

- It is impossible to design the system by using only the queuing network theory.

For this challenging point, we aim to integrate the queuing network theory into the simulation-based method and iterate a design process; then, we will propose a methodology which can exactly simulate the transportation delay and thus estimate the efficiency of the proposed methodology.

2 Transportation System in a Port Container Terminal

2.1 AGV transportation system

In this study, the AGV transportation system is divided into three areas, namely, the quay, transport, and container yard areas (Fig.1). In this system, AGVs continue to circulate until they successfully complete all tasks by the following procedure:

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

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

step3 The AGV arrives at the assigned location. If it encounters another AGV in its working path, this AGV goes onto the passing path; then, this passing path becomes a working path.
step4 If the ATC is already at the handling point, the AGV will transfer the container to ATC. Otherwise, if the ATC is already engaged, the AGV will wait at this point.
step5 The ATC goes to storage point in the assigned location to store the container.
step6 The AGV that has handled a container goes back to the quay area. (back to step1)

In this system, two different types of ATCs are working at the same location. Therefore, they can cross each other with working.

2.2 Combinatorial optimization problem

Design objects

The parameters of the design object in this study are described as the following:
- The number of AGVs
- The number of ATCs
- The number of passing paths (buffers)

All containers should successfully be transported from the container ship to the container yard area within a limited amount of time. In these constraints, the minimum number of agents that satisfy the requirement is used as a performance function.

Assumption of the transportation system

In this study, each location becomes the destination of a container by 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 due to the fixed scale of a berth.

3 Queuing Network Theory

3.1 Cyclic queuing network

In the closed queuing network, the number of agents is constant since agents can neither arrive nor leave the system, but, rather, circulate repeatedly through the various nodes at all times [5]. 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 [6]. Fig.2 indicates the state of transition in the system from step n (Fig.2a) to step $n+1$ (Fig.2b).

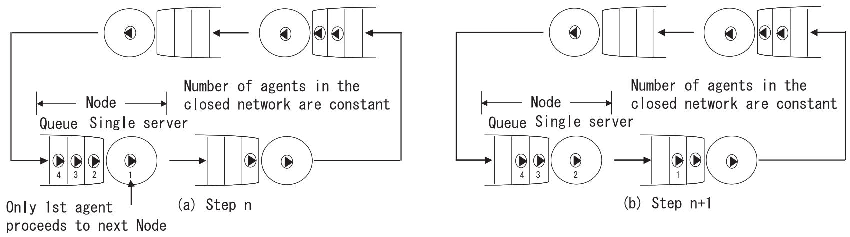

Fig. 2. A state transition diagram in the cyclic queuing network composed of a single server. Only the first agent proceeds to the next node; then, the next queuing agent (the second agent in that queue) goes into the single server, and the third and fourth agents proceed forward in the queue.

3.2 Performance evaluation method

Ottjes *et al.* and Duinkerken *et al.* used some performance indicators when they designed the ACTs using a specific transport simulator [7][8]. Similarly in our study, 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 input parameters. 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.

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

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

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

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

$$G_{[j]}(K) = \sum_{x_1+\cdots+x_{j-1}+x_{j+1}+\cdots+x_N=K} \prod_{i=1, i\neq j}^{N} q_i(x_i) \tag{5}$$

where,
K: The Number of AGVs
ρ_{j1}: The traffic parameter
h_{j1}: The number of relative arrivals of AGVs
$G(K)$: Normalization constant
$G_{[j]}(K)$: Normalization constant of j-complement in the network
N: The number of nodes
x_j: The number of AGVs around the node$j$

$q_j(x_j)$: Convolution parameter

where the ρ_{j1} is given by {the number of relative arrivals of AGVs at a certain node j} × {the service time at a certain node j} and the 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 a single 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 from 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 given by removing the jth node in the closed queuing network, that is, $G_{[j]}(K)$ is obtained by procedure of the $G(K)$ described below [5]:

Define the $G(K)$ and $q(K)$ arrays; then, execute the following procedure after initializing these arrays:

$$G(x) \leftarrow \begin{cases} 1, \; x = 0 \\ 0, \; x \neq 0 \end{cases}$$

for ($j = 1$; $j <=$ N; j++) {

  for ($x = 0$; $x <=$ K; x++) {

$$q(x) \leftarrow \begin{cases} \dfrac{h_j^x}{x!}, & \|x\| \leq S_j \\ \dfrac{\|x\|}{S_j! S_j^{\|x\|-S_j}} \dfrac{h_j^x}{x!}, & Sj < \|x\| \end{cases}$$

  }

  for ($k =$ K; $k >= 0$; $k--$) {

$$G(k) \leftarrow \sum_{0 \leq y \leq k} q(y) G(k-y)$$

  }

}

where, S_j is the number of servers working at each node.

4 System Design

4.1 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 transportation tasks are completed.

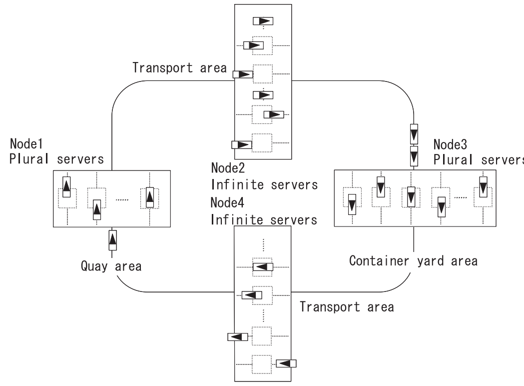

Fig. 3. Modeling the transportation system

4.2 Transport specifications of AGV and ATC

Table1 indicates the specifications for the AGV and ATC. Fig.4 is the transportation route for the AGVs. It is assumed that the AGVs go through the central path in the quay area 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], respectively. On the other hand, the loading/unloading and handling time of the container crane and ATCs is fixed because of the above assumption; therefore, in this study, the time at nodes 1 and 3 are given as 60 [s] and 30 [s], respectively. However, if the ATC is not at the handling point when the AGV arrives, the AGV will need to wait at this point.

Table 1. Specification of the AGV and ATC

	AGV(full)	AGV(empty)	ATC(full)	ATC(empty)
Max. velocity [m/s]	5.56	6.94	2.25	2.0
Rotational velocity [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

4.3 Design algorithm

Fig.5 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 transportation delay by the AGV friction.

The service time at each node and the number of the container cranes and ATCs are inputted as initial parameters. After that, the throughput is obtained by the eq.(2). 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 based on the performance function. However, if it does not satisfy the requirement, 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.

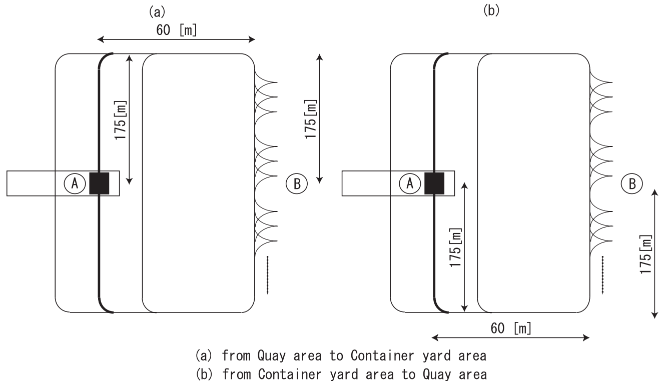

Fig. 4. Modeling of transport routing

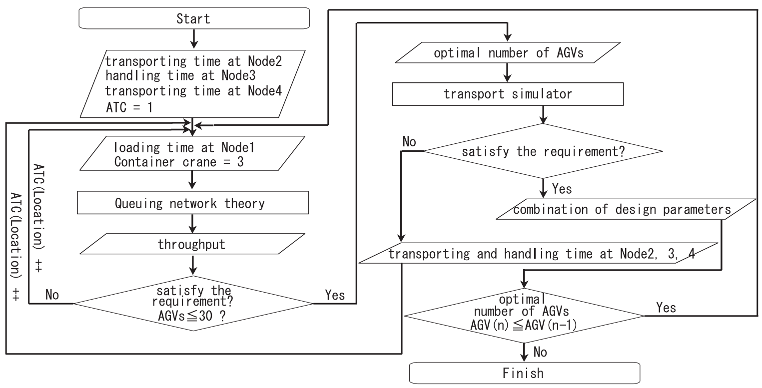

Fig. 5. Design algorithm by using the queuing network theory

The transportation simulator then operates based on the derived number of AGVs to evaluate whether or not this theoretical result also satisfies the requirement. If the simulation result also satisfies the requirement, the combination of optimal design parameters is 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 are calculated by a simulator, and then the calculated time can be used as input parameters.

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 $n-1$.

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

4.5 The combination of design solutions

Table2 indicates the number of AGVs at each node in the case of the design solutions are obtained. The average number of AGVs at node3 is less than the number of locations (6 and 7). Therefore, the number of buffers is designed as “0” (See Table3).

Table 2. Average number of AGVs at each node

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

Table3 indicates each combination of optimal design solutions and time cost at each node (See the case a and b). The increase in the time is noticeable as the number of AGVs increases. Here, there is a trade-off between the throughput that depends on the number of AGVs and the time needed by the node. Therefore, there are cases in which increasing the number of AGVs worsens the transport efficiency.

Table 3. The combination of design parameters and time cost at each node

Case	ATC	AGV	Buffer	Transporting time Node2, 3, 4 [s]
a	12	17	0	178, 45, 144
b	14	16	0	170, 36, 140

4.6 Consideration

Consideration of design solutions by the throughput

Fig.6 indicates the throughput obtained by this design result. It can be confirmed that more than the optimal number of AGVs derived by this proposed design algorithm could satisfy the requirement. From the simulation result, the throughput is confirmed to be (a) 120.1 and (b) 126.6. From this result, we consider that the proposed design methodology is available.

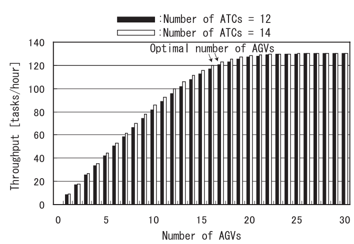

Fig. 6. System throughput

Consideration of computational cost

If we solve this combinatorial optimization problem by using the all search algorithm of the simulation-based optimization method, we must consider all the combinations of design solutions: 30 AGVs $\times$ 10 ATCs $\times$ 2 buffers equal to 600 times of simulation cost is needed. Correspondingly, in our proposed method, the total simulation cost required until the solutions are derived is just 15 times. From this result, this proposal design methodology is able to derive the solutions with a few simulations.

5 System Performance Evaluation

5.1 Traffic intensity

The traffic intensity at nodes 1 and 3 are evaluated in each design solutions. As shown in Table4, in the system which is designed by the derived solution, it can be located that bottleneck is in the quay side.

Table 4. Traffic Intensity at Nodes 1 and 3

Case	Node1 [%]	Node3 [%]
a	92.4	44.5
b	91.9	33.7

Fig.7 indicates the traffic intensity curve at nodes 1 and 3 while the number of AGVs in the system increases. 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.

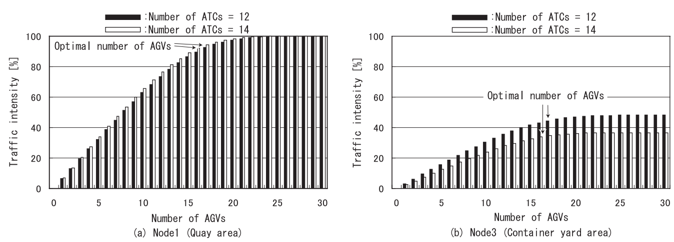

Fig. 7. Performance evaluation by the traffic intensity curve

5.2 Average number of AGVs at each node

Fig.8 indicates the average number of AGVs at each node while the number of AGVs increases. Thus, Fig.8 indicates the rough behavior of AGVs. From Fig.8(b) and (d), we can derive the number of transporting AGVs at nodes 2 and 4. From Fig.8(a) and (c), we can derive the number of loading/unloading and handling AGVs and of queuing AGVs at nodes 1 and 3. This shows that adding more AGVs to obtain more throughput leads the system to breakdown due to the existence of bottleneck.

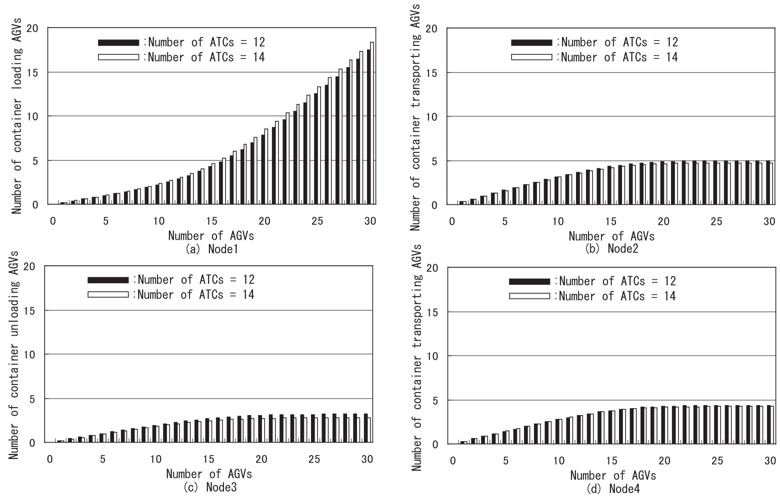

Fig. 8. The number of AGVs at each node

6 Conclusion and Future Work

In this paper, the design methodology and performance evaluation of an actual AGV transportation system are described. For this purpose, we integrated the queuing network theory into the simulation-based optimization method. The methodology was then proposed, which can simulate the transport delay exactly and evaluate the efficiency of the proposed methodology.

As future work, it would be necessary to design actual multi-agent transportation systems by modeling agents other than AGVs on the basis of a certain probabilistic distribution of the rough behavior of such agents. In addition, this methodology will be applied at actual container terminals so that the efficiency of the system can be verified.

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