Design of an Automated Transportation System in a Seaport Container Terminal for the Reliability of Operating Robots

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***Abstract*— For the design of an automated transportation system in an actual seaport container terminal, it is necessary to take into consideration the maintenance of operating robots (AGV: Automated Guided Vehicle and ATC: Automated Transfer Crane). For this purpose, we develop an operation model in which each robot enters a maintenance mode while operating on the basis of its reliability. We also aim to design the mean time between failure (MTBF) which is a kind of a measure of robot performance on the basis of the robots' reliability as well as the number of robots. However, this is a combinatorial design problem. Therefore, we propose a design methodology in order to derive one combinatorial design solution for a given demand by considering a system management cost that includes a system construction cost and a penalty cost. The designed systems are evaluated on the basis of the system management costs. Finally, we present the validity of the proposed design methodology and designed systems.**

***Index Terms*— Seaport container terminal, automated transportation system, AGV, ATC, MTBF, design, reliability.**

I. INTRODUCTION

In recent years, the volume of container trade has increased significantly [1]. In this regard, concern is increasing regarding the automation of seaport container terminals. Following this trend, several studies have investigated automation on container-handling systems [2]. We have so far aimed at highly efficient automated transportation systems in seaport container terminals with robots and focused on an automated guided vehicle (AGV) transportation system such as that shown in Fig.1. As a result, the authors and some other researchers have designed (I) the number of robots [3]; (II) the system layouts [3] [4]; (III) system management models [5] [6] [7] [8]; (IV) an existing transportation system for improvement [9]; and (V) robot performance [10].

Material-handling systems in manufacturing and production environments have already been designed on the basis of system reliability [11]. As for an automated transportation system in a seaport container terminal, especially due to salt erosion, it is important to take into account the endurance and fault-tolerance of the whole system. Here, we define an activity to ensure the robots' endurance and fault-tolerance as the maintenance. In design methodologies (I)∼(V), however, the maintenance of the operating robots in the systems has not been considered. In other words, only the cost for the construction of a system and demand, i.e., the system throughput ([twenty-foot equivalent unit (TEU)/hour] = required number of handling containers / required operating time), has been considered as a constraint. In order to design an automated transportation system from a more practical point of view, it is necessary to take into account the maintenance of operating robots, that is, their reliability.

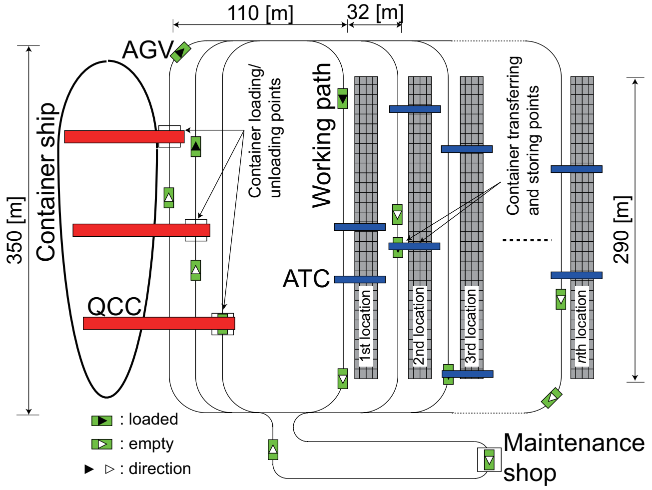

Fig. 1. Horizontal AGV Transportation System in a Seaport Container Terminal (top view)

In this paper, as shown in Fig.1, we use AGVs and automated transfer cranes (ATCs) as the operating robots. For the system, we develop an operation model in which the AGVs and ATCs enter a maintenance mode while operating on the basis of their reliability. Thus, the robots continue to operate and be maintained regularly. Regarding the effect on the system of taking into account the reliability of the operating robots, this effect depends on the type of a robot. That is to say,

- a system is generally very expensive if maintenance-free, high-performance robots are used; and
- the maintenance of operating robots takes up the most time because more maintenance is required when cheap, low-performance robots are used. Furthermore,
- putting weight on the reliability of the operating robots takes time for maintenance. Hence, the cost-effectiveness of a system with many operating robots is reduced. On the other hand,
- if operating robots are not maintained at all until they break down, a system must stop working. Consequently, the system does not meet the demand; a large penalty is inflicted on the port authorities.

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Therefore, as for the maintenance, we decide the timing on the basis of the degree of reliability as a criterion. Here, the degree of reliability represents the probability of a robot operating normally over a period of time. This parameter is determined based on the mean time between failure (MTBF). In order to design the system that meets the demand at low cost but covers the maintenance of the operating robots, our objective is to determine the optimum number of robots and design their MTBF adequately for a given demand in consideration of the reliability of the operating robots. However, this is a combinatorial design problem. Therefore, we propose a design methodology in order to derive one combination of them for a demand as the combinatorial design solution. The designed systems are evaluated on the basis of the system management costs. Finally, we present the validity of the proposed methodology and designed systems.

II. CHALLENGES

For this study, we design and manage a transportation system that meets a demand while maintaining the AGV and ATC as shown in Fig.1 in consideration of their reliability. To meet these objectives, there are the following challenges:

1) In managing the system, it is necessary to maintain the operating robots efficiently as well as other container-handling operations.
2) The system should be designed on the basis of the careful consideration of a penalty cost caused by robot maintenance.

For challenge 1), we develop a maintenance model in which mutual operation substitutability of the AGV and ATC is utilized. Specifically, each robot is maintained regularly on the basis of its degree of reliability while performing given tasks in the model. The AGVs, while not on a path, enter the maintenance shop, as shown in Fig.1, where they are maintained. The ATCs, for their maintenance, go to the end of container storage locations, where they are maintained.

For challenge 2), we introduce a system management cost constraint even though the focus, up to this point, has been limited to the system construction cost and demand. Here, the system management cost includes the system construction cost on the basis of the number of operating robots and the penalty cost caused by the robot maintenance.

III. AUTOMATED TRANSPORTATION SYSTEM IN A SEAPORT CONTAINER TERMINAL

A. AGV Transportation System

We have shown the effectiveness of a horizontal AGV transportation system as an automated transportation system in a seaport container terminal [3]. Thus, this system shown in Fig.1 is the design objective. An AGV transports a container on a single unidirectional path. In the horizontal AGV transportation system, the container locations are horizontally arranged for the container ship. A location consists of 320 container storage spaces, i.e., 4 rows, 20 bays, and 4 tiers.

For the system design, we divide it into three kinds and four areas, namely, the quay area, two transportation areas, and the container yard area. Quay container cranes (QCCs) operate in the quay area, AGVs operate in the transportation areas, and ATCs operate in the container yard area. Since two ATCs of different sizes are operating at one location, they can cross each other. As for the number of QCCs, it is not a design parameter because the scale of a berth is fixed. There are three operating QCCs in the quay area.

TABLE I

OPERATION PERFORMANCE OF AGV, ATC, AND QCC

AGV		loaded / empty
max. transportation speed	[m/s]	5.56 / 6.94
acceleration	[m/s^2]	0.15 / 0.15
deceleration	[m/s^2]	0.63 / 0.63
ATC		
max. moving speed	[m/s]	2.5
acceleration	[m/s^2]	0.1
deceleration	[m/s^2]	0.4
storing time	[s]	30
transferring time	[s]	30
QCC		
loading/unloading time	[s]	60

B. Procedure for Container-Handling Operations

Following the procedures (1)∼(7), the operating robots, which are the AGVs and ATCs continue to perform their tasks until they successfully complete all containers loaded in a container ship.

1) After an AGV arrives at a QCC, the QCC loads a container from the container ship to the AGV.
2) The AGV transports the container through the transportation area from the quay area to a target location in the container yard area.
3) The AGV calls an ATC on an adjacent work path to the location.
4) If there is an idling ATC, the ATC is selected and called to a container transferring position as a cooperation partner, or else, the AGV keeps calling.
5) The AGV begins container transferring to the ATC after the ATC arrives at the position.
6) The AGV that has completed transferring goes back to a QCC through the transportation area.
7) The ATC to which the container has been transferred stores it at a storage position and then waits for the next task.

Here, in 1), regardless of the position of the containers in a container ship, we assume that the container loading time by the QCC is constant. The container transferring time from the AGV to ATC in 5) and container storing time by the ATC in 7) are also constant regardless of the position on a location. In 2), a target location of a container is determined with the use of a management model [8]; then, the container is transported by the AGV. A container storage position on a location and a target QCC are randomly determined.

C. Operation Performance

Table I shows the operation performance of AGV, ATC, and QCC [13].

From Table I, the container loading time by the QCC, the container transferring time from the AGV to ATC, and the container storing time by the ATC are 60, 30, and 30 seconds, respectively.

IV. OPERATION MODEL IN THE MAINTENANCE MODE

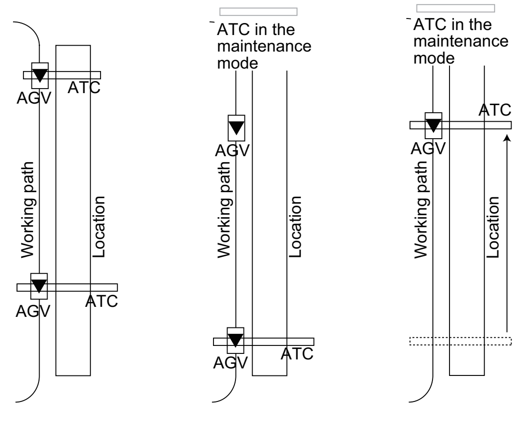
In general, there are four maintenance activities, as follows: 1. improved maintenance for initial failure; 2. preventive maintenance for decreased function; 3. corrective maintenance; and 4. improved maintenance for performance upgrade. Savsar has proposed a policy in order to decide the maintenance timing of operating machines with several MTBFs in a flexible manufacturing system [12]. He also has described the importance of doing the preventive maintenance.

Therefore, in this study, we do the same maintenance on the basis of the MTBF of the operating robots. In other words, based on the degree of reliability, each robot stops operating and enters the maintenance mode when its degree of reliability is under a threshold value. As for the robots' maintenance, even if another AGV or ATC is already in the maintenance mode, an AGV or ATC also enters the maintenance mode if its degree of reliability is under a threshold value. Thus, multiple AGVs and ATCs enter the maintenance mode at the same time depending on the circumstances. Here, we defined the maintenance mode as follows: an operating robot comes into a state to be maintained. Since there is a limited number of maintainers, in this paper, only one AGV and ATC in the maintenance mode are maintained. An AGV which transferred a container to an ATC goes to the maintenance shop (see Fig.1), and an ATC which stored a container moves to the end of the location so as not to obstruct the operations of other robots. They are then maintained. The time for the maintenance is constant.

In the case that multiple AGVs and ATCs enter the maintenance mode at the same time, as we described in II, it is necessary to maintain the robots efficiently in order to take advantage of the mutual substitutability of the operation among robots that have a similar function.

If an AGV is maintained on a path, the AGV becomes an obstacle to other AGVs. To solve this problem, we parallelized the system by providing a maintenance shop as described above. By doing this, the transportation system is able to keep operating except in the case that all AGVs are in the maintenance mode and go to the maintenance shop. Here, an AGV that arrives at the maintenance shop first is maintained according to the First-In First-Out (FIFO) rule.

On the other hand, since there are two ATCs at one location, as described in III-A, even if an ATC at the location is in the maintenance mode, another ATC is able to perform its task instead. However, if both ATCs at the location are in the maintenance mode at the same time, the flow of incoming AGVs is disrupted on the adjacent work path to the location. Hence, the whole system operation might be interrupted. To solve this problem, we contrived the following rules; thus, the ATCs are maintained on the basis of the rules.



(a) (b) (c)

Fig. 2. Operation Model in the Maintenance Mode

- If there is a location where two ATCs are both in the maintenance mode, one ATC of two on the location is maintained by priority.
- If either ATC operates at every location, an ATC that enters the maintenance mode first is maintained by rotation.

Fig.2 shows container transferring and storing operations among the AGV and ATC in case one ATC at the location enters the maintenance mode. In Fig.2(a), two ATCs are operating; then, in Fig.2(b), one (small) ATC is in the maintenance mode. For this situation, the other (large) ATC moves up to a target position to support the other operation with the waiting AGV (see Fig.2(c)). With regard to the container transferring and storing operations at a location, it is possible to keep the system working to a maximum extent by using the operation rules even if one ATC is in the maintenance mode.

V. DESIGN METHODOLOGY

A. Design Parameter

We have shown an efficient system layout and management model for given demands. Therefore, we use a horizontal transportation system [3] and the following management model: after the container transportation and storage destinations are planned on the basis of the equivalent transportation rule, the container storage tasks are scheduled so that the total moving distance of the ATC is minimized; then, the AGV selects and calls out the ATC with the use of workspace-based selection rule on the work path [8]. Hence, the following objectives are the design parameters in this paper.

- Number of operating robots, such as AGVs and ATCs.
- MTBF of the operating robots.

As for the number of AGVs and ATCs, in order to avoid adding more robots than necessary in the design process, we determine the maximum number of robots in advance. To design the number of robots, we use a hybrid design methodology in which mathematical and simulation models are used in conjunction [3]. The number of QCCs operating in the transportation system is three as a fixed parameter, as we described in III-A.

B. Reliability of the Operating Robots

In this paper, we assume that the failure rate of an operating robot ($\lambda(t)$) in the transportation system at a time t is constant (see Eq.(1)), in other words, it follows an exponential distribution. Thus, the degree of reliability ($R(t)$), which is the probability that the robot has not failed by time t, is derived from Eq.(2). We decide the robot maintenance timing on the basis of the degree of reliability.

$$\lambda(t) = \lambda_0 \tag{1}$$

$$R(t) = e^{-\lambda_0 t} \tag{2}$$

The MTBF of the operating robot, the failure rate of which follows an exponential distribution, is derived from Eq.(3). From Eq.(1), Eq.(2), and Eq.(3), the failure rate of an operating robot $\lambda(t)$ can be derived from the reciprocal number of the MTBF; thus, we calculate the degree of reliability with the use of the MTBF.

$$MTBF = \int_0^\infty R(t)\, dt = \int_0^\infty e^{-\lambda_0 t}\, dt = \frac{1}{\lambda_0} \tag{3}$$

In this paper, we assume several grades of the MTBF. We then design the number of operating robots and the MTBF after due consideration of the system management cost and given demand while maintaining the robots on the basis of their degree of reliability $R(t)$. Here, the $R(t)$ of an operating robot, which was once maintained, is reset to one ($R(t) = 1$) at a time.

C. System Management Cost

In order to derive one combinatorial design solution from several combinations of design parameters that meet a given demand, we take into account the system management cost (Eq.(4)) in the design process. The system management cost C_m represents a cost that includes the system construction cost C_c derived on the basis of the design parameters and the penalty cost C_p inflicted on the port authorities.

$$C_m = C_c + C_p \tag{4}$$

Eq.(5) represents the system construction cost. Since we assumed that the number of QCCs is fixed, the construction cost consists of an equipment cost with the use of the number of AGVs and ATCs and a development cost on the basis of the difference of a grade of the MTBF. Eq.(6) represents the penalty cost that is derived by multiplying the number of containers left in the container ship by a penalty factor in case that the operating robots in the constructed system do not complete all tasks within a required operation time.

$$C_c = \alpha \times \gamma_{agv} \times AGVs + \beta \times \gamma_{atc} \times ATCs, \tag{5}$$

$$C_p = \sum_{i=1}^{n_u} \delta n_{con\_i}, \tag{6}$$

TABLE II

MTBF OF AGV AND ATC

	MTBF$_{agv}$ [hour]	MTBF$_{atc}$ [hour]
low	50	40
normal	100	80
high	150	120
higher	200	160

where

α	equipment cost factor of the AGV,
β	equipment cost factor of the ATC,
γ_{agv}	development cost factor of the AGV,
γ_{atc}	development cost factor of the ATC,
δ	penalty cost factor,
n_u	the number of unfinished container ships,
n_{con_i}	the number of containers left in the container ship (ith).

As for the number of unfinished incoming container ships n_u, this parameter is incremented in case that the system does not complete all tasks within a required time. For instance, a case of containers that was left in three container ships of j incoming container ships is represented as $n_u = 3$.

VI. SYSTEM DESIGN

A. Design Conditions

The maximum numbers of AGVs and ATCs in the design process are 30 and 20, respectively. As for the MTBF of the operating robots, we referred to the literature [14] and [15]. Thus, as shown in TableII, the MTBFs of AGV and ATC are divided into four grades as follows: low, normal, high, and higher. These are the design objectives. Each operating robot is maintained at time t when the degree of its reliability is less than 0.9, that is, $R(t) \leq 0.9$. Here, the initial degree of reliability of each operating robot at the start of a simulation is given randomly as follows: $0.9 < R(t) \leq 1.0$. Maintenance time, 0.5 [h] and 0.4 [h], is required for the AGV and ATC. In this paper, since we design the system in consideration of preventive maintenance, we assume that the operating robots do not break down in the system.

The cost factors written in V-C are given as follows: $\alpha = 1$ and $\beta = 2$, based on the life cycle cost and equipment cost of the robots, and $\gamma_{agv} = \gamma_{atc} = 0.8$ (low), 1.0 (normal), 1.5 (high), and 2.0 (higher), based on the four-grade development cost of the MTBFs. The penalty cost factor is given as $\delta = 0.05$. These are variable values according to the port authorities.

A required throughput is given to the transportation system as a demand. The total number of containers in a container ship, that is, the number of tasks, is 600 [TEU]; the demands are 10$\sim$130 [TEU/hour]. Here, because there is a 320 [TEU] container space at one location, two locations, i.e., at least four ATCs, are needed in the system.

B. Design Process

Fig.3 shows the design process. The design process consists of the following two steps: 1. deriving the combinations of the design parameters that meet a given demand, and 2.

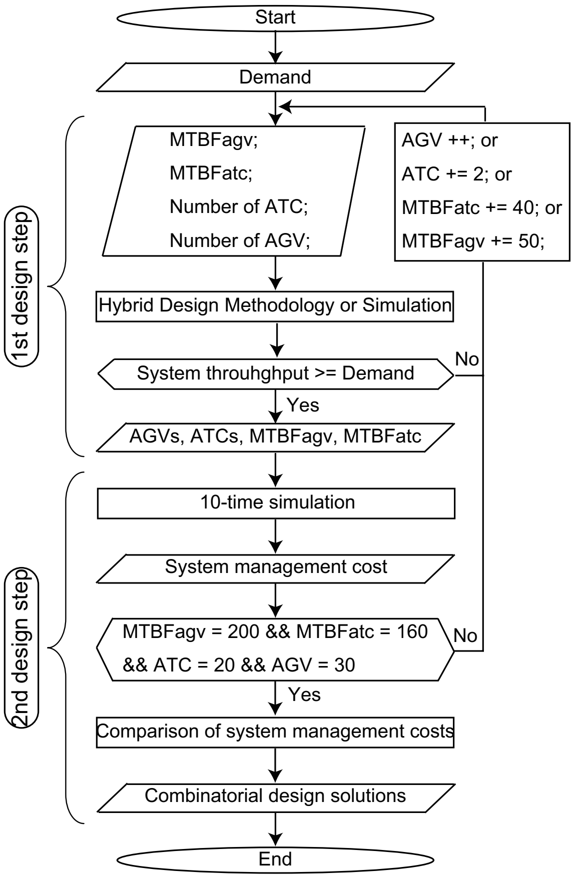


Fig. 3. Design Process Using a Simulation

TABLE III

COMBINATORIAL DESIGN SOLUTIONS

Demand	AGVs	ATCs	MTBF$_{agv}$	MTBF$_{atc}$	C$_m$	C$_d$
10	2	4	50	40	8	12
20	3	4	50	40	8.8	13.2
30	4	4	50	40	9.6	14.4
40	6	4	50	40	11.2	14.8
50	8	4	50	40	12.8	17.2
60	8	4	100	40	16.1	19.1
70	9	4	100	40	19.8	19.2
80	11	4	100	40	23.4	21.2
90	13	4	100	40	26.3	26.5
100	16	4	100	40	31.9	39
110	14	4	100	120	42.8	46.3
120	15	6	100	120	49.4	62
130	22	12	100	80	68.6	95.3

deriving one combinatorial design solution on the basis of the system management cost after simulations with the use of the derived design parameters are done.

In the first step, we derive the design parameters using the hybrid design methodology if no AGV and ATC enter the maintenance mode during a 600-task operation. If the AGVs and ATCs often enter the maintenance mode during such operations, we derive the design parameters by using a simulation-based exhaustive search method. In the second step, in order to consider the system management cost, we do a 10-time simulation for 10 incoming container ships with the use of the design parameters derived from the first step.

In the following, we describe the detailed design process using a simulation-based exhaustive search method. Here, design process 4), which corresponds to the first step, is terminated if the derived number of AGVs is not decreased for the incremented number of ATCs; then, the process skips to design process 8), which corresponds to the second step.

1) A demand is given to the transportation system.
2) The initial MTBFs of the AGV (low) and ATC (low) and the number of AGVs (one) and ATCs (four) are inputted.
3) A transportation simulation is conducted.
4) If the system does not meet the demand, any one of the AGV, ATC, MTBF$_{atc}$, or MTBF$_{agv}$ is incremented within its limits as described in VI-A.
5) If the system meets the demand, a combination of the design parameters is derived.
6) A 10-time simulation with the use of the derived design parameters is conducted.
7) The system management cost is derived.
8) If the four design parameters are not stretched to their limits, any one of the AGV, ATC, MTBF$_{atc}$, or MTBF$_{agv}$ is incremented again.
9) If the four design parameters are stretched to their limits, the derived system management costs are compared.
10) The design parameters that construct the system at the lowest cost are derived as the combinatorial design solution.

C. Combinatorial Design Solution

TableIII shows the derived combinatorial design solutions for the given demands. In the table, C$_d$ refers to the difference of the lowest system management cost C$_m$ designed with the use of the combinatorial design solution and the highest management cost in the derived combinations of the design parameters.

Under the design conditions, we can derive the combinatorial design solutions with the use of the “low” MTBFs of AGV and ATC for demands up to 50 [TEU/hour]. This result shows that it is possible to develop a highly efficient transportation system without using a high-performance AGV and ATC for the lower demands. For demands above 60 [TEU/hour], the number of AGVs and ATCs that enter the maintenance mode is increased in the constructed systems with the use of the “low” MTBFs of AGV and ATC. In consequence, the derived number of AGVs and ATCs is increased, and then, combinations of the design parameters with the upgraded MTBF$_{agv}$ and MTBF$_{atc}$ to “normal” or “high” are derived as the combinatorial design solutions.

From the result, we can see that it is possible to design a highly efficient transportation system by considering the reliability of the operating robots and designing their MTBFs in accordance with the given demands in addition to the appropriate number of robots. Thus, the validity of the design methodology and the designed systems is shown.

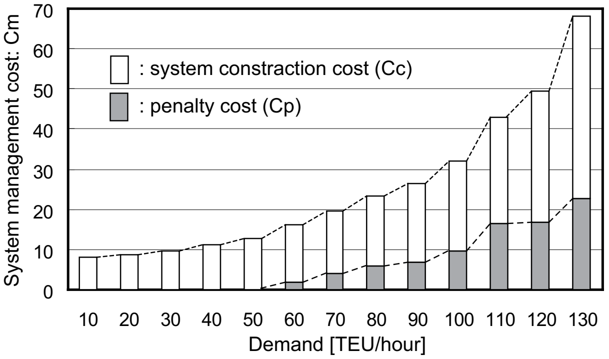


Fig. 4. System Management Cost for Given Demands

TABLE IV

SIMULATION RESULT WITH COMBINATORIAL DESIGN SOLUTIONS

Demand	Number of unfinished container ships	Number of containers left in a ship [TEU]	Ratio of the penalty cost [%]
10	0	0	0
20	0	0	0
30	0	0	0
40	0	0	0
50	0	0	0
60	1	35	10.8
70	1	84	21.3
80	1	120	25.7
90	1	137	26.1
100	2	190	29.8
110	5	336	38.4
120	6	329	33.9
130	2	452	33.2

D. Discussion

Fig.4 shows the system management cost derived with the use of the combinatorial design solutions for the given demands. From Fig.4, we can see that the penalty costs are zero in the system management cost for demands up to 50 [TEU/hour]. This is because the systems completed all tasks during the 10-time simulation. However, the penalty cost increases for the demands more then 60 [TEU/hour]. This result shows that the effect of the penalty cost on the system management cost for the higher demands increases gradually. Therefore, it is important to consider the degree of reliability of the operating robots; the transportation system must be designed on the basis of a system management cost that includes the penalty cost.

TableIV shows the number of unfinished incoming container ships in the 10-time simulation, the total number of containers left in the container ship(s), and the ratio of the penalty cost to the system management cost for the demands over the 10-time simulation. From the result, although the penalty cost is increased when the demand increases, we can see that the ratio of the number of containers left in the container ship(s) to the total number of containers (600 × 10 [TEU]) is about 7.5 [%] even for a demand of 130 [TEU/hour]. It is possible to underestimate the penalty cost if the penalty cost factor, δ, is less than the value which was given in this design. Furthermore, it took about 30 seconds to conduct the 10-time simulation with the use of a Pentium Xeon 5160 3.0 [GHz] CPU.

VII. CONCLUSION

In this paper, we designed an automated transportation system in a seaport container terminal for the reliability of operating robots. In order to take the robots' reliability into account, we developed a maintenance model in which the operating robots, i.e., AGV and ATC with MTBF, are maintained on the basis of their degree of reliability while operating. In addition, we proposed a design methodology to derive the number of AGVs and ATCs and their MTBFs as a combinatorial design solution for a given demand. Finally, we presented the validity of the proposed design methodology and the designed systems.

In future works, not only the maintenance, we will address unpredictable situations, such as the malfunction of the operating robots, and have to consider operation models.

VIII. ACKNOWLEDGMENTS

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