Integrated Design Methodology for an Automated Transportation System in a Seaport Terminal

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***Abstract*— Automation of transportation systems and promotion of the operations are becoming an international demand on seaport container terminals. For this issue, we propose an integrated design methodology. In other words, in addition to the design of the appropriate number of machines, efficient system layout, and system management models, we attempt to design machines' specifications, which are operating in an automated transportation system. The objective of this study is to maximize the system efficiency while minimizing the changes of the specifications. Therefore, we evaluate the specifications based on the system throughput of the constructed system; then, make clear the impacts of the specifications on the system. Finally, for imposed demands, we design highly efficient transportation systems. From the construction costs and design results, we show a need to take into consideration the machines' specifications.**

***Index Terms*— Integrated design methodology, seaport AGV transportation system, machines' specifications.**

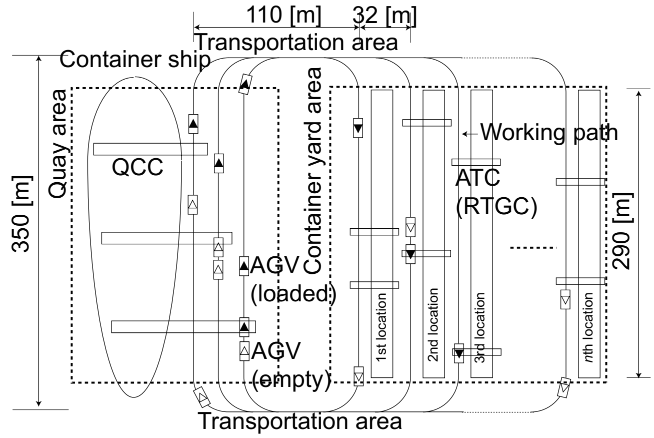

Fig. 1. Horizontal AGV transportation system in a seaport container terminal (top view)

I. Introduction

The amount of container trade, especially in Asia, has increased significantly in recent years [1]. Following this trend, several studies have investigated automation on shipment handling systems from various viewpoints [2]. In the systems, there are several kinds of handling equipments operating automatically. In this paper, we define the equipments as "machines." Additionally, these machines have their own operation functions, e.g., loading, transportation, storage, etc. The grades of these functions are defined as "specifications," such as high speed loading, normal speed transportation, and low speed storage specifications.

For the realization of a highly efficient automated transportation system in a seaport container terminal, we have so far investigated design methodologies for the automated guided vehicle (AGV) transportation system as shown in Fig.1. Using this methodology, we have achieved the following objectives: 1. a design of the appropriate number of operating machines [3], 2. evaluation and design of typical transportation layouts, such as vertical and horizontal ones [3]. From the results, we have presented the effectiveness of the horizontal transportation system under given demands [3]. Additionally, we have focused on 3. a design of management models of the transportation systems [4] [5]. We have shown the importance to take into account the management aspects in addition to the objectives 1 and 2. On the other hand, we have also improved an existing transportation system using the proposed design methodology [6]. In the results, we have made clear that the system capacity is defined based on the given conditions and machine's specifications.

Liu *et al* have developed seaport container terminal systems in which various kinds of conceivable machines are working; then, effectiveness of the systems were evaluated based on the transportation time [8]. From the result, they have shown the most efficient machines and system for a given demand. Gottwald Port Technology has focused on automated container terminals, which are located in Rotterdam, Netherlands and Hamburg, Germany, and then, they developed management strategies for a highly efficient AGV transportation system.

Those conventional studies, however, have not referred to the design of the machines' specifications. These specifications were given in advance according to the kinds of the operating machines [7]. Through the joint studies, we have so far found out that port designers and authorities would like to make clear if the specifications have impacts on the system, beforehand. This is because they have to grasp a need to downgrade or upgrade of the specifications for various demands. Therefore, in order to increase system efficiency, appropriately design of the machines' specifications, which are operating in the system is an essential.

Fisher *et al* have proposed a methodology to select appropriate types of material handling equipment by applying heuristic rules [10]. From the literatures on the trend of the recent worldwide automated seaport container terminal, we can see that quay container cranes (QCCs) in a quay

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side, AGVs in the transportation side, and automated transfer cranes (ATCs) in a container yard side are generally used [1] [2].

Therefore, in this study, we assume that there are three kinds of machines, i.e., QCC, AGV, and ATC; then, we attempt to develop a highly efficient transportation system by evaluating the machines' specifications. For this purpose, we propose an integrated design methodology. In this methodology, we first change the specifications, and then, evaluate the effects on the system throughput. Finally, we design the machines' specifications in addition to the objectives mentioned above. Here, transportation demand is defined as follows: demand = required throughput [Twenty-foot Equivalent Unit (TEU)/hour] = total number of transported containers / required container transportation time.

Compare to the conventional studies, which have been focusing on the design objectives 1 $\sim$ 3 described above, we additionally refer to the 4th design objective: 4. a design of machines' specifications. Thus, this design methodology, which includes the objectives 1 $\sim$ 4 is defined as an integrated design methodology, in this paper.

II. AGV Transportation System in an Automated Seaport Container Terminal

A. Seaport AGV Transportation System

Fig.1 shows the horizontal AGV transportation system, which is the design object of this study. In this system, the container locations are horizontally arranged for the container ship. The location consists of 640 container storage spaces, i.e., 4 rows, 20 bays, and 8 tiers.

For the design, the system is first divided into three kinds and four areas, namely, the quay area, two transportation areas, and the container yard area. As we described in section I, the QCCs, AGVs, and rubber tire-type ATCs, i.e., rubber-tired gantry cranes (RTGCs) are operating in the system. Here, let us assume that two RTGCs of different sizes are operating at one location. As for the number of QCCs, it is not a design parameter because the scale of a berth is fixed. We assume that there are three operating QCCs in the quay area in this study.

The containers carried by the container ship are unloaded by the QCCs in the quay area; then, they are transported by AGVs. Finally, the containers are transferred to RTGCs; stored by them in the yard area. The machines' specifications for the operation are shown in TableI. In this paper, each machine operates based on the normal specifications unless a change of a specification is clearly shown by the authors.

B. Operation Procedure

The AGVs continue to circulate until they successfully complete all container transportations by the following procedure:

1) A QCC unloads and loads a container from the container ship to an AGV.
2) The AGV transports the container to a handling point.
3) An RGTC moves to the container handling point.

TABLE I
MACHINES' SPECIFICATIONS OF AGV, RTGC, AND QCC

AGV		loaded / empty
Maximum transportation speed	[m/s]	5.56 / 6.94
Acceleration	[m/s^2]	0.15 / 0.15
Deceleration	[m/s^2]	0.63 / 0.63
RTGC		
Maximum moving speed	[m/s]	2.5
Acceleration	[m/s^2]	0.1
Deceleration	[m/s^2]	0.4
Storing speed	[s]	30
Transferring speed	[s]	30
QCC		
Loading/Unloading speed	[s]	60

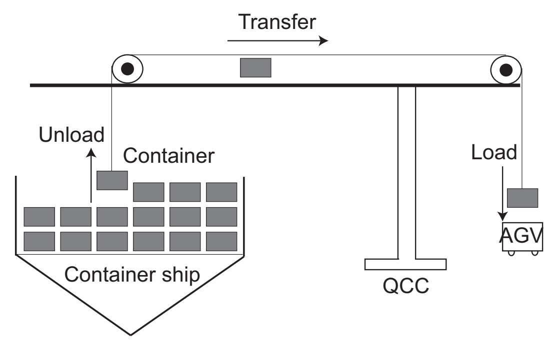


Fig. 2. Loading/Unloading operation by QCCs in the quay area (side view)

4) The AGV transfers the container to the RTGC at the point.
5) The AGV that has completed the transfer goes back to a QCC; the RMGC to which the container has been transferred stores it at the storage point and then waits for the next task. Back to the procedure 1).

C. Operations by the Machines in Each Area

Containers that are shipped to the quay side in the terminal are unloaded/loaded, transported, and stored to their destination in the yard area by the operating machines. Here, let us define the operations in each area as follows:

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

Transportation area: This area represents the AGV transportation route between the quay and container yard areas.

Container yard area: An AGV transfers a container to an RTGC which operates on a location; then, the RTGC stores the container into the location as shown in Fig.4.

III. Challenges

In this study, we aim at an integrated design of the AGV transportation system. In other words, we take into consideration the machines' specifications as follows: how much the system efficiency is increased with the changes in a machine and the specification.

TABLE II

MACHINES SPECIFICATIONS DIVIDED FOUR LEVELS: SLOW, NORMAL, FAST, AND FASTER

Specification		slow	normal	fast	faster
Loading/Unloading speed by QCC	[s]	75	60	45	30
Maximum transportation speed by AGV (loaded/empty)	[m/s]	4.17/5.20	5.56/6.94	8.34/10.41	12.88/13.88
Maximum moving speed by RTGC	[m/s]	1.93	2.25	3.87	4.5
Transferring/Storing speed by RTGC	[s]	45/45	30/30	22.5/22.5	15/15

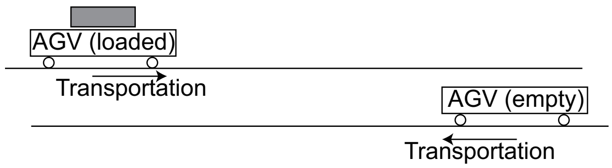


Fig. 3. Transportation by AGVs in the transportation area (side view)

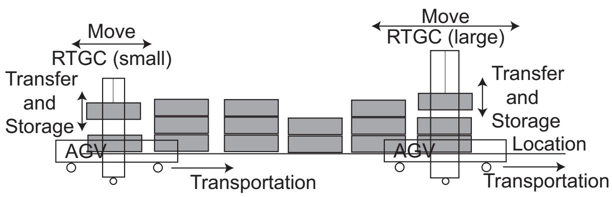


Fig. 4. Transferring/Storing operation by RTGCs in the container yard area (side view)

However, it is difficult to change all specifications from the viewpoints of the technical and economic issues. Therefore, designers need to increase system efficiency as much as possible while minimizing the changes of the specifications. This is the objective of this study. Additionally, since we aim to design various parameters that are mutually interdependent, we have to solve a combinatorial design problem. This is the challenge of this study. Conventional studies have evaluated the effectiveness of the transportation systems in which AGVs and automated lifting vehicles (ALVs) are operating as the machines, respectively [11] [12]. These studies, however, include the following problems: 1. effects on the systems by the changes in the machines' specifications have not referred because the specifications of the AGV and ALV for the operation had already given [11], 2. appropriate numbers of AGVs, ALV, and their specifications for imposed demands were not derived [12].

For the challenge described above, we make clear if a specification has an impact on the system efficiency. In the result, we will show that which machine and the specification should be downgraded or upgraded. For this purpose, we focus on the following four machines' specifications as the evaluation objectives: loading speed of the QCC, transportation speed of the AGV, moving speed of the RTGC, and transferring/storing speed of the RTGC. We use the machines whose specifications are downgraded or upgraded based on the evaluation result; then, we design the number of machines for the demands.

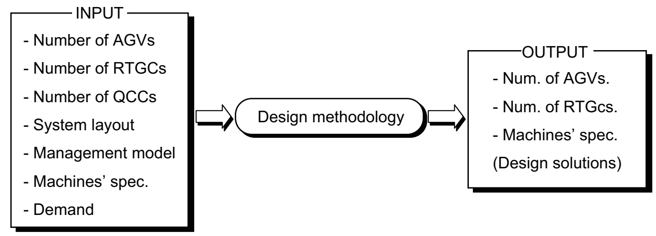


Fig. 5. Input and output parameters (design solutions)

IV. DESIGN METHODOLOGY

A. Parameters

Since this study focuses on an integrated design methodology for the AGV transportation system, we take into consideration the seven input parameters as shown in Fig.5. A demand is a parameter imposed by port authorities.

We have shown the efficient system layout and management model in the conventional studies [3] [5]. Based on the results, for the design objectives 2 and 3 described in section I, we adopt the horizontal system layout as shown in Fig.1 and the following management model: "the AGV selects and calls out the RTGC with the use of workspace-based selection on the work path under container storage scheduling after the container transportation and storage destinations are planned on the basis of equivalent transportation [5]." Thus, the system layout and management model are given in this design. As described in II-A, the number of QCCs is also given as three. Therefore, for a demand, we will derive the following design solutions as output parameters:

- Number of operating machines, i.e., AGVs and RTGCs
- Machines' specifications

Note that even though we focus on two parameters described above, this combinatorial design problem has the following solution space: number of demands $\times$ combination of the numbers of machines $\times$ combination of the machines and the specifications.

As for the input number of machines above, we derive appropriate numbers of AGVs and RTGCs. For this purpose, we apply a hybrid design methodology using a mathematical model and simulation model [3].

B. Machines' Specifications

The following four machine's specifications are the evaluation objectives. As shown in TableII, four machines' specifications are divided into four grades, such as slow, normal, fast, and faster. This division represents downgrade and upgrade designs of the machines' specifications. Here, the specifications described in TableI are defined as the normal. Other specifications that are not described here are as same as the ones described in TableI.

- Loading/Unloading speed of the QCC
- Maximum transportation speed of the AGV
- Maximum moving speed of the RTGC
- Transferring/Storing speed of the RTGC

In the design process, we construct the small-scale, medium-scale, and large-scale systems in which the machines are operating based on the changed specifications. We will then compare and evaluate the derived system throughput.

C. Cost Model

The numbers of AGVs, RTGCs, and QCCs, which consists of the transportation system are evaluation factors. In this study, we use the following cost model in the design process; then, we compare and evaluate the construction costs.

Construction cost $= \alpha\times$AGVs $+\beta\times$RTGCs $+\gamma\times$QCCs

Here, α, β, and γ denote the weighting factors of the costs of the AGV, RTGC, and QCC. Based on the life cycle cost of the machines and the setting cost, these factors are determined as follows: $\alpha : \beta : \gamma = 1 : 2 : 4$. Additionally, in order to consider four cost differences, that is, development cost for the upgrade and the downgrade cost. Therefore, we assume that $0.8\times$ factor for the downgrade (slow), $1.5\times$ factor, and $2.0\times$ factor for the upgrade (fast and faster), respectively.

V. Integrated System Design

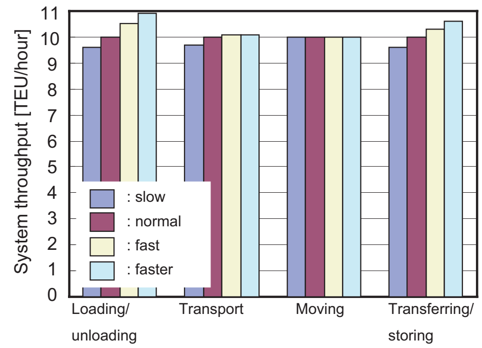
A. Design Process and Evaluation Condition

Through the following design process, a combination of the number of AGVs and RTGCs, and a specification are designed for an imposed demand.

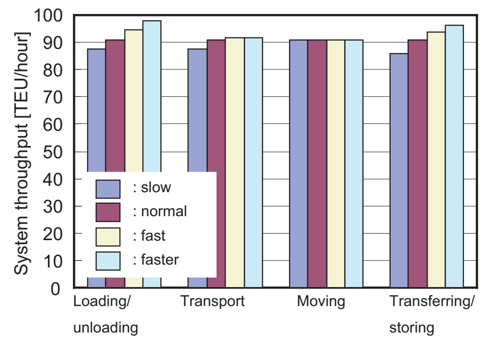
1) Change of the specifications
2) Comparison and evaluation of the effects of the changes on the system throughput
3) Upgrade or downgrade of the specifications based on the results of the design process 2)
4) Machines implementation
5) Derivation of the number of machines for a demand
6) Construction of the designed systems and comparison of the costs for the demand
7) Design of a combination of the number of machines and a specification, which meets the demand with the lowest construction cost

In this design process, only one specification is changed at a time, and others are normal. For the evaluation of the machines' specifications as described in the design process 2), in this study, we consider the specifications as the parameters; then, in the following three AGV transportation systems, we use the machines whose parameters are changed. Here, the numbers in parentheses denote the number of QCCs, AGVs, and RTGCs, from left side.

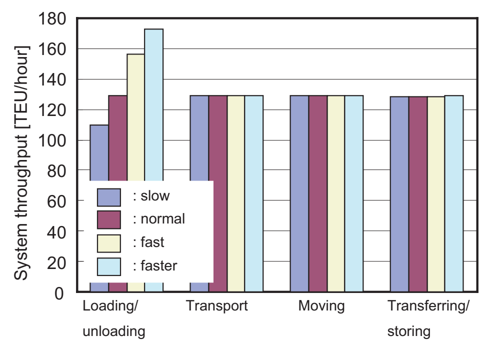
- Small-scale AGV transportation system: (3, 1, 2)



(a) Small-scale AGV transportation system



(b) Medium-scale AGV transportation system



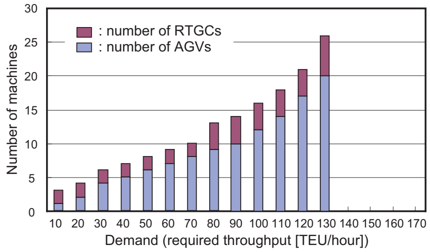
(c) Large-scale AGV transportation system

Fig. 6. Comparison results of each AGV transportation system

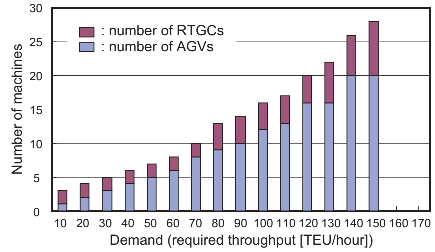
- Medium-scale AGV transportation system: (3, 10, 6)
- Large-scale AGV transportation system: (3, 20, 10)

B. Comparison and Evaluation of the System Throughput

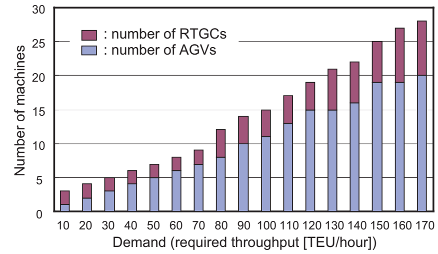
Fig.6 shows the comparison results of the system throughput when each specification was changed in the small, medium, and large-scale AGV transportation systems, respectively. In the figures, the horizontal axis indicates the specifications and the vertical axis indicates the throughput when each specification is changed to slow, normal, fast, and faster.



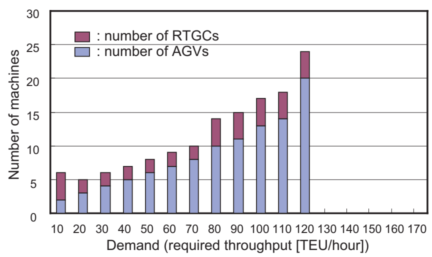
(a) All specifications: normal



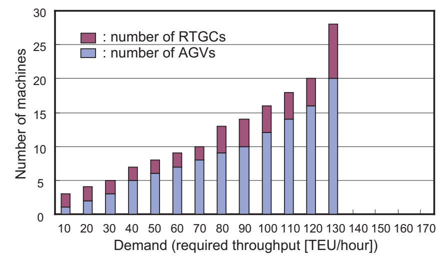
(b) QCC loading/unloading speed: fast



(c) QCC loading/unloading speed: faster



(d) AGV transportation speed: slow



(e) RTGC moving speed: slow

Fig. 7. Number of AGVs and RTGCs derived for the demands when a specification is changed

From Fig.6(a) and Fig.6(b), we can notice that the loading/unloading speed of the QCC and the transferring/storing speed of the RTGC are the parameters, which have the effects on the throughput of the small-scale and medium-scale transportation systems. Meanwhile, there are little effects of the maximum AGV transportation speed and the maximum RTGC moving speed on the throughput. The result occurs because in some cases the QCCs become idle when the AGVs do not return to them. For this result, even if we upgrade the maximum transportation speed, we can not increase the system throughput because of the system layout. In other words, the AGV's specification and system layout, i.e., a configuration of a transportation route are interdependent parameters, and they effect on the system together. Compare to the AGV's specification, we found out that the system layout has more impact. As for the maximum moving speed, under the management model given in this study, we do not identify the effect because an RMGC can arrive at the handling point before an AGV arrives in many cases. Therefore, we can conclude that such sophisticated AGV and RMGC are not needed for the systems. For the large-scale system as shown in Fig.6(c), we conclude that the change of the loading/unloading speed is the parameter, which has the highest impact on the throughput compare to the other parameters.

From the results above, under the given assumptions and conditions, the loading/unloading speed of the QCC has the highest impact on the transportation system. Also, the specifications on the maximum transportation and moving speeds of the AGV and RTGC have little impacts on the system. These results indicate that the loading/unloading speed needs to be developed. Meanwhile, it is possible to downgrade the specifications on the maximum transportation speed of the AGV and moving speed of the RTGC.

C. Comparison of the Number of AGVs and RTGCs

Fig.7 shows the derived number of AGVs and RTGCs (vertical axis) for the imposed demands (horizontal axis), under all specifications are normal; the loading/unloading speed is fast; the loading/unloading speed is faster; the transportation speed is slow; and the moving speed is slow.

In this design, total number of containers, which is required for transportation is 600 [TEU]. Again, note that other parameters except a parameter shown in each caption of the figure are set to normal.

The conventional system that consists of the normal machines' specifications can not meet the demands over 140 [TEU/hour] as shown in Fig.7(a). Compare to this system, the systems in which the loading/unloading speeds are developed and upgraded to fast and faster meet the demands up to 150 and 170 [TEU/hour], respectively. From the results shown in Fig.7(a) and Fig.7(d), we can notice that the derived numbers of AGVs and RTGCs are almost the same, although the system meets the demands only up to 120 [TEU/hour] (see Fig.7(d)). The system in which the moving speed of the RTGC is downgraded to slow meets the demands up to 130 [TEU/hour] as shown in Fig.7(e). A tendency of the number of AGVs and RTGCs for the demands are largely similar to the tendency shown in Fig.7(a).

D. Combinatorial Design Solution

Fig.8 shows the construction costs derived from the cost model described in IV-C based on the derived numbers of

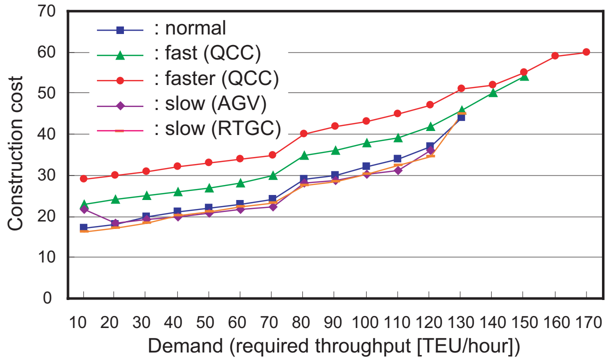


Fig. 8. Comparison of the construction costs

TABLE III
COMBINATORIAL DESIGN SOLUTION

Demand	Machine & spec.	AGV	RTGC	Cost
10	RTGC: slow	1	2	16.2
20	RTGC: slow	2	2	17.2
30	RTGC: slow	3	2	18.2
40	AGV: slow	5	2	20.0
50	AGV: slow	6	2	20.8
60	AGV: slow	7	2	21.6
70	AGV: slow	8	2	22.4
80	RTGC: slow	9	4	27.4
90	RTGC: slow	10	4	28.4
100	AGV: slow	13	4	30.4
	RTGC: slow	12	4	30.4
110	AGV: slow	14	4	31.2
120	RTGC: slow	16	4	34.4
130	normal	20	6	44.0
140	QCC: fast	20	6	50.0
150	QCC: fast	20	8	54.0
160	QCC: faster	19	8	59.0
170	QCC: faster	20	8	60.0

AGVs, RTGCs, and QCCs as shown in Fig.7. In the figure, the horizontal axis indicates the transportation demand and the vertical axis indicates the total construction cost. By comparing the construction costs for a demand, we evaluate the system, which is constructed at the lowest cost, and then, we finally derive a combinatorial design solution, i.e., the number of AGVs, RTGCs, and the machine's specification (see Table III).

From Fig.8 and Table III, for the lower demands, we do not see a need to develop and upgrade the specification on the loading/unloading speed of the QCC from the viewpoint of the economic issue. Meanwhile, the downgrade costs of the AGV and RTGC effect on the construction costs. As a result, compare to the conventional AGV transportation system in which the machines with the normal specifications are operating, the costs are lower. However, these systems can not meet the demands over 140 [TEU/hour], hence, the system is required to develop and upgrade the specification of the QCC for the higher demands.

For these results, we confirm the validity of the design of the specifications, i.e., upgrade for higher demands or downgrade for lower demands, appropriately.

VI. CONCLUSION

In order to develop a highly efficient seaport AGV transportation system, we proposed an integrated design methodology. In particular, we focused on the design of the number of machines and the specifications. Using the methodology, we downgraded or upgraded the specifications respectively; then, we designed the number of AGVs, RTGCs, and their specifications for the demands with the use of the machines. In the result, under the given assumptions and conditions, we finally concluded that there is a case in which it is needed to upgrade or downgrade a machine's specification appropriately for a demand in addition to the number of machines. Moreover, we presented that the system in which the machines are operating with the designed specifications is more efficient than a conventional system in which the machines are operating with the normal specifications. This design result caused the highly efficient AGV transportation system while minimizing the changes of the specifications.

In future works, we will design an automated transportation system in a seaport container terminal taking into consideration the reliability, such as maintenance and breakdown of operating machines.

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