

# Performance Design of Operating Robots in a Seaport Container-Handling System

Satoshi Hoshino and Jun Ota

**Abstract**—In order to provide a highly efficient container-handling system in a seaport terminal, for a given constraint, i.e., demand, we take into account the performance of operating robots, such as quay container cranes (QCCs), automated guided vehicles (AGVs), and rubber-tired gantry cranes (RTGCs) in addition to the number of robots, as design objectives. However, this is a combinatorial design problem. Therefore in this paper, we propose a design methodology with the use of a hybrid design process which had been proposed for designing the number of robots. By using this methodology, we design two objectives, that is, the number of robots and their performance for a given demand. Finally, we present the validity of the proposed methodology by comparing and evaluating construction costs of two systems, which are designed with the use of the proposed design methodology and a design methodology which does not take into account the robots performance. Moreover, we discuss the designed robots performance in terms of the system bottleneck.

## I. INTRODUCTION

The amount of container trade has increased significantly in recent years [1]. Following this trend, several studies have investigated automation on shipment handling systems [2]. In the systems, various kinds of container-handling robots are operating automatically. Additionally, these operating robots have their own operation functions, e.g., unloading/loading, transportation, storing, etc. The grades of these functions are defined as “performance,” such as high speed unloading/loading, normal speed transportation, and low speed storing performance.

For the realization of a highly efficient seaport container-handling system, we have so far focused on an automated guided vehicle (AGV) transportation system (see Fig.1) and proposed design methodologies; then, we have tackled the following challenges: (I) design of the appropriate number of operating robots [3], (II) evaluation and design of typical layouts, such as vertical and horizontal ones [3], (III) design of management models of the systems [4] [5], and (IV) improved design of an existing transportation system [6]. From the results (I) and (II), we have presented the effectiveness of the horizontal transportation system under given design conditions. From the result (III), we have shown the importance to take into account the management aspects in addition to the objectives (I) and (II). For an existing system, (IV), we have shown the importance of designing a

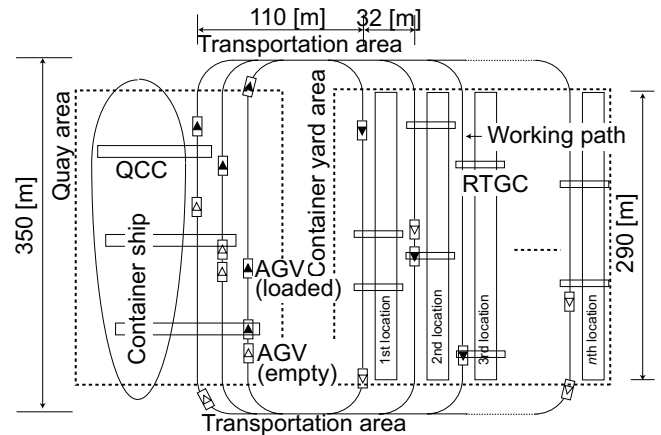


Fig. 1. Horizontal AGV transportation system in a seaport container terminal (top view)

bottleneck part in the system even if the robots performance are fixed. Liu *et al* have developed seaport container terminal systems in which various kinds of conceivable operating robots are working; then, effectiveness of the systems were evaluated based on the transportation time [7]. 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 [8].

Those conventional studies, however, have not referred to the design of the robots performance. These performance were given in advance according to the kinds of the operating robots, as listed in [9]. Through the joint studies, we have so far found out that port designers and authorities would like to make clear if a robot performance has the impact on the system, beforehand. This is because they have to identify a need to downgrade or upgrade of the robot performance for various demands. Therefore, in order to increase system efficiency, an appropriately design of the robots performance is an essential.

For this issue, we have proposed an integrated design methodology for an AGV transportation system in a seaport container terminal [10]. However, only one performance was focused and addressed in the design process; this is not enough to consider the impacts of the robots performance on the system. Therefore, in order to taken into account the impacts of the robots performance on the system, we propose a new design methodology; we design the robots performance for the container-handling operation. Finally, we present the validity of the proposed methodology by

S. Hoshino is with the Chemical Resources Laboratory, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, JAPAN [hoshino@pse.res.titech.ac.jp](mailto:hoshino@pse.res.titech.ac.jp)

J. Ota is with the Department of Precision Engineering, School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, JAPAN [ota@prince.pe.u-tokyo.ac.jp](mailto:ota@prince.pe.u-tokyo.ac.jp)

comparing and evaluating construction costs of two systems, which are designed with the used of the proposed design methodology and a design methodology which does not take into account the robots performance. Moreover, we discuss the designed robots performance in terms of the system bottleneck.

## II. CHALLENGES

In this paper, we aim to design the seaport container-handling system with the operating robots for given demands by considering the robots performance and the number of robots. In other words, we take into account the following issue: how much the system efficiency is increased with the changes in the number of robots and their performance. For this issue, it is an unrealistic approach to upgrade or downgrade the all robots performance for a demand in terms of technological and economic problems. Therefore, designers need to increase system efficiency as much as possible by changing the performance which have/has the impacts on the system adequately. Additionally, since we aim to design various parameters, such as the number of operating robots and their performance 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 several container-handling systems in which AGVs and automated lifting vehicles (ALVs) are working as the operating robots, respectively [11] [12]. In evaluating the robots performance, the container loading time in a quay side and container storing time in a yard side were used as the cycle time. These studies, however, include the following problems: 1. the impacts on the systems by the changes in the robots performance have not been referred because the performance of AGV and ALV for the container-handling operations were fixed [11], hence, 2. appropriate number of AGVs, ALV, and their performance for given demands were not derived [12].

For the challenges, we improve a design process which had been proposed for designing the number of robots for a given demand in order to take into account the robots performance in addition. In the proposed design methodology, for a given demand, the number of robots and their performance are the design objectives. As for the robots performance, the whole combination of them are evaluated; then, based on their combination, the number of robots are derived with the use of the hybrid design process. In order to derive one combinatorial design solution for a combinatorial design problem, we introduce a cost model which includes an equipment cost and a development cost of the operating robots.

## III. SEAPORT CONTAINER-HANDLING SYSTEM

### A. Seaport AGV Transportation System

Fig.1 shows the horizontal AGV transportation system in a seaport container terminal, which is the design object of this study. In this system, the container storage locations are horizontally arranged for the container ship. The location

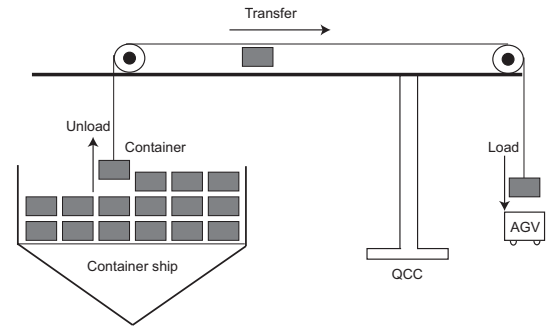


Fig. 2. Loading/Unloading operation by QCCs in the quay area (side view)

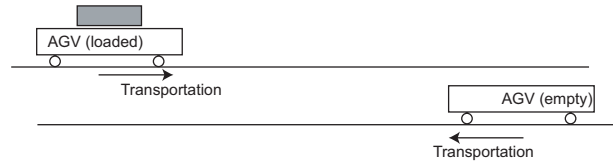


Fig. 3. Transportation by AGVs in the transportation area (side view)

consists of 640 container storage spaces, i.e., 4 rows, 20 bays, and 8 tiers.

In designing, the system is first divided into three kinds and four areas, namely, the quay area, two transportation areas, and the container yard area. In this system, quay container cranes (QCCs), AGVs, and rubber-tired gantry cranes (RTGCs) are working for the container-handling operations. These are the operating robots. 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.

### B. Container-Handling Operations in Each Area

Containers that are shipped to the quay area in the system are unloaded, loaded, transported, transferred, and finally stored to their destinations in the container yard area by the operating robots, such as the QCCs, AGVs, and RTGCs. Fig.2, Fig.3, and Fig.4 show the container-handling operations. Here, let us define the container-handling operations in each area as follows:

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

**Transportation area:** This area represents the AGV transportation route between the quay and container yard areas as shown in Fig.3. The AGV transports the container in this area.

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

### C. Container-Handling Procedure

Following the procedures (1)~(7), the operating robots continue to perform their tasks until they successfully com-

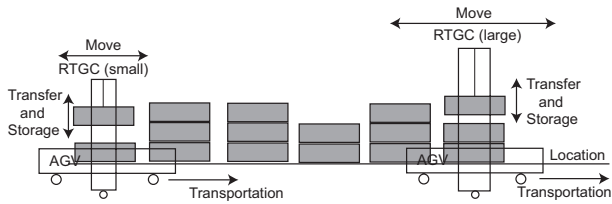


Fig. 4. Transferring and storing operations by RTGCs in the container yard area (side view)

TABLE I  
ROBOTS PERFORMANCE: AGV, RTGC, AND QCC

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

plete all containers in a container ship.

- 1) After an AGV arrives at a QCC, the QCC unloads and 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 RTGC on an adjacent work path to the target container storage location.
- 4) If there is an idling RTGC, the RTGC 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 RTGC after the RTGC arrives at the transferring position.
- 6) The AGV that has completed transferring goes back to a QCC through the transportation area.
- 7) The RTGC to which the container has been transferred stores it at the storage position and then waits for the next task.

#### D. Robots Performance (normal)

Table I shows the normal robots performance, i.e., AGV, RTGC, and QCC, which are given on the basis of a literature [9].

In this table, the robots performance regarding the container-handling operations are maximum transportation speed of the AGV, maximum moving speed, storing speed, and transferring speed of the RTGC, and loading/unloading speed of the QCC, respectively.

## IV. DESIGN METHODOLOGY

### A. Parameters

In the design methodology, the following parameters, such as the design constraint, demand, input/output (design)

parameters, and design criterion are addressed.

- design constraint
  - demand
    - \* required number of handling containers ([TEU])
    - \* required container-handling time
- input (design) parameters
  - number of operating robots
  - robots performance
- design criterion
  - system construction cost (cost model)
- output (design) parameters
  - number of operating robots
  - robots performance

In this paper, the AGV, RTGC, and QCC are used as the operating robots in the system; the number of AGVs and RTGCs and the performance of AGV, RTGC, and QCC are designed. Note that even though we focus on two design parameters, this combinatorial design problem has the following solution space: number of demands  $\times$  combination of the number of robots  $\times$  combination of the robots performance.

### B. Design Parameters

1) *Number of operating robots*: As for the design of the number of robots, we focus on the following two parameters:

- number of AGVs; and
- number of RTGCs.

Here, in order to avoid adding more robots, AGVs and RTGCs, than necessary in the design process, we determine the maximum number of AGVs and RTGCs beforehand. The number of QCCs operating in the system is three as a fixed parameter, as we described in III-A.

2) *Robots performance*: The following four robots performance for container-handling are the design parameters:

- loading/unloading speed of the QCC;
- maximum transportation speed of the AGV;
- maximum moving speed of the RTGC; and
- transferring and storing speeds of the RTGC.

As shown in TableII, four robots performance are divided into four grades, such as slow, normal, fast, and faster. This division represents downgrade and upgrade designs of the robots performance for a given demand. Here, the performance described in TableI are defined as the normal. Other performance, such as acceleration and deceleration of the AGV and RTGC, are as same as the ones described in TableI, in other words, these are constant values. In the design process, the whole combination of the robots and their performance are evaluated.

### C. Design Criterion

The number of AGVs, RTGCs, and QCCs which compose the system, and their performance are the evaluation elements. In the design process, since the design solutions (the number of AGVs and RTGCs) of the integer value are derived, there is a case several design solutions which meet

TABLE II

ROBOTS PERFORMANCE DIVIDED INTO FOUR GRADES: SLOW, NORMAL, FAST, AND FASTER

Performance	AGV	RTGC (moving)	RTGC (transferring & storing)	QCC
	[m/s]	[m/s]	[s]	[s]
slow	4.0/5.0	2.0	45/45	75
normal	5.56/6.94	2.25	30/30	60
fast	8.0/9.0	3.0	22.5/22.5	45
faster	10.0/11.0	4.0	15/15	30

a demand are derived. Moreover, even for the same demand, according to a combination of the robots performance, different number of AGVs and RTGCs are derived.

Therefore in this paper, we introduce the following cost model, namely the construction cost, as a design criterion in the design process; then, we derive one combinatorial design solution, that is the number of AGVs and RTGCs and the robots performance by comparing and evaluating the construction costs.

$$\begin{aligned} \text{Cost} = & \alpha \times \delta_{AGV} \times AGVs + \\ & \beta \times \delta_{RTGC_m} \times \delta_{RTGC_{ts}} \times RTGCs + \\ & \gamma \times \delta_{QCC} \times QCCs, \end{aligned}$$

where,  $\alpha$ ,  $\beta$ , and  $\gamma$  denote the equipment cost factors of the AGV, RTGC, and QCC.  $\delta_{AGV}$ ,  $\delta_{RTGC_m}$ ,  $\delta_{RTGC_{ts}}$ , and  $\delta_{QCC}$  are the development cost factors for the upgrade or downgrade design on the basis of the difference of the grade of the robots performance.

#### D. Design Process

Fig.5 shows the design process from a demand to a combinatorial design solution. A part surrounded by the dashed line shows a hybrid design process which has been proposed in the past design methodology for deriving the number of robots for a demand [3]. In this process, as design parameters, the number of AGVs and RTGCs are calculated with the use of the queuing network model in order to prune search space; the mathematical result is then inputted into the simulation model, and finally, the combinatorial number of AGVs and RTGCs which meet a demand is derived.

In this process, first, a demand is given as a design constraint, then, three QCCs, horizontal system layout, and management model are given. After that, a combination of the number of AGVs, RTGCs, and the performance of AGV, RTGC, and QCC which meet the demand are derived. As for the performance of AGV, RTGC, and QCC, the whole combination of them are evaluated in the design process; then, for the demand, the number of AGVs and RTGCs on the basis of the combination of the robots performance are derived within the hybrid design process. In this hybrid design process, any one of the AGV and RTGC are incremented within its limit. In case of that the system does not meet the demand even if the number of AGVs and RTGCs are stretched to their limits, the combination of the robots performance is changed, and then, the design process is iterated. As for the robots

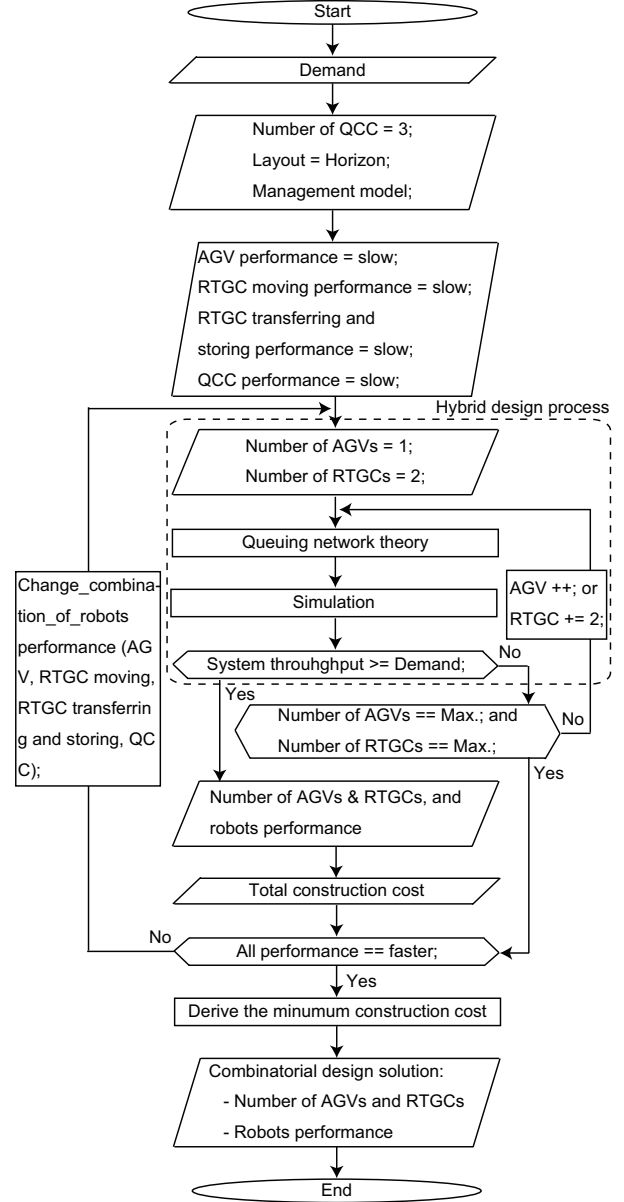


Fig. 5. Proposed design process

performance, if the system in which the AGV, RTGC, and QCC that operate with performance “faster” does not meet the demand, in other words, the number of AGVs and RTGCs are not derived, this design process is terminated.

If the number of AGVs and RTGCs which meet the demand are derived, the combination of the design parameters, number of AGVs, RTGCs, and the robots performance, is derived; then, the system construction cost is derived on the basis of the cost model. If the whole robots performance are not faster, any one of them is changed and the design process is iterated. Else, the derived construction costs in the design process are all compared, and finally the combination of the design parameters which construct the system with the lowest cost is derived as the combinatorial design solution.

TABLE III  
COMBINATORIAL DESIGN SOLUTIONS: NUMBER OF AGVs, RTGCs, AND ROBOTS PERFORMANCE

Demand [TEU/hour]	Num. of AGVs	Num. of RTGCs	AGV: transportation	RTGC: moving	RTGC: transferring & storing	QCC:
10	2	2	slow	slow	slow	slow
20	3	2	slow	slow	slow	slow
30	4	2	slow	slow	slow	slow
40	5	2	slow	slow	slow	slow
50	6	2	slow	slow	slow	slow
60	7	2	slow	slow	normal	normal
70	8	2	normal	slow	normal	slow
80	10	4	slow	slow	normal	slow
90	11	4	slow	slow	normal	slow
100	13	4	slow	slow	normal	slow
110	14	4	slow	normal	normal	normal
120	18	4	slow	slow	normal	normal
130	20	4	slow	normal	normal	fast
140	17	6	normal	slow	normal	fast
150	20	6	slow	normal	normal	fast
160	19	6	normal	normal	normal	faster
170	20	8	normal	slow	normal	faster
180	20	6	normal	slow	faster	faster

## V. SYSTEM DESIGN

### A. Design Condition

The maximum number of AGVs and ATCs in the design process are 30 and 20, respectively. Thus, in case of that the system does not meet a demand even if the number of AGVs and RTGCs are stretched to their limits, 30 and 20, and the robots performance are all faster, the design process is terminated.

As for a demand given to the system, we assume that a container ship with 600 containers arrives at the quay area as shown in Fig.1. In other words, the required number of handling containers is 600 [TEU]. However, we consider various required container-handling time, hence, the demands are given to the system as follows until the system does not meet the demand: 10 [TEU/hour], 20 [TEU/hour], 30 [TEU/hour],  $\dots$ .

The cost factors described in IV-C are given as follows:  $\alpha = 1$ ,  $\beta = 2$ , and  $\gamma = 4$ , based on the life cycle cost and equipment cost of the robots, and  $\gamma_{agv} = \gamma_{atc} = 0.9$  (low), 1.0 (normal), 2.0 (fast), and 3.0 (faster), based on the four-grade development cost of the robots performance.

### B. Combinatorial Design Solution

Table III shows the derived combinatorial design solutions: the number of AGVs, RTGCs, and the performance of AGV, RTGC, and QCC. Under the given design condition, the design solutions up to demand 180 [TEU/hour] were derived.

From the result, up to demands 50 [TEU/hour], we can see that the system with the whole robots performance “slow” is constructed at lower cost compare to the conventional system in which all robots performance is set to normal. As the demand is increased, although the number of AGVs and RTGCs increase and each robot performance is upgraded, we can see that not all performance, only several important performance which have impacts on the system throughput are adequately

designed. Thus, the systems with lower cost are constructed by changing the robots performance adequately.

From the trend of variation of the design solutions for the demands, we can notice that there is a case that the number of AGVs or RTGCs decreases for the increased demands. Moreover, there is a case that a robot performance which was once designed to normal is again designed to slow. This is because that the combination of the design parameters with the lowest cost was derived as the combinatorial design solution. In other words, even if the number of robots are increased or decreased, it is possible to design the system at lower cost by downgrading or upgrading the robots performance. Consequently, the combination of the design solutions with the lowest cost was derived; thus, the trend of the design solutions was as shown in Table III.

For demands from 60 to 100 [TEU/hour], the performance of the RTGC on the container transferring and storing operations were designed to normal from slow. The reason of this result is that a bottleneck was occurred in the system because of the following two reasons: 1. a relationship between the number of AGVs and RTGCs; 2. the container transferring and storing operations of the RTGC. Hence, the performance of the RTGC needed to be upgraded.

For demands more than 110 [TEU/hour], the performance of the QCC on the container loading operation was designed to normal, fast, or faster. This is because the bottleneck in the container yard area was reduced by increasing the number of AGVs and RTGCs, and upgrading the performance of the RTGC on the container transferring and storing operations. Thus, the bottleneck was shifted to the quay area. In other words, the AGVs frequently arrive at the QCCs; then, the operation on the container loading of the QCCs caused the bottleneck in the system.

On the other hand, the maximum transportation speed and moving speed of the AGV and RTGC were designed to slow or normal. This is because the number of AGVs

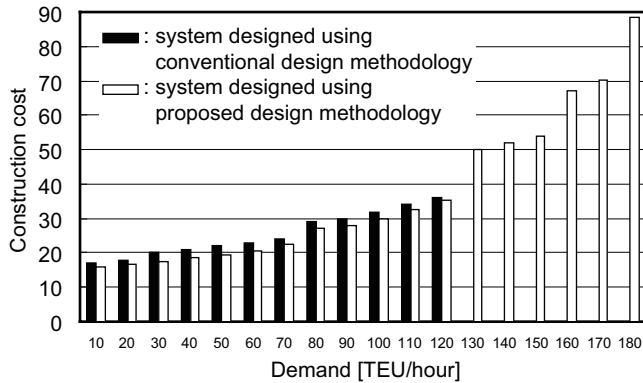


Fig. 6. Comparison result of the construction costs

is the design parameter and the AGV could not reach its maximum transportation speed in the system even if the performance was upgraded. As for the maximum moving speed of the RTGC, under the given management model, the RTGCs arrived at container transferring positions before the AGVs arrive; thus, these robots performance did not have the impacts on the system.

From the result and discussion above, the requirement of that increasing system efficiency as much as possible while minimizing the changes of the robots performance, is finally achieved.

### C. Comparison and Evaluation of the Designed System Construction Costs

Fig.6 shows the comparison result of the construction costs for the demands. There are two systems which were designed with the use of (1) the proposed design methodology and (2) a design methodology which does not take into account the robots performance. In the system designed with the use of the design methodology (2) without considering the robots performance, the robots performance are all set to normal as described in Table I.

From the result, we can see that no design solution was derived for demands more than 130 [TEU/hour], because only the number of AGVs and RTGCs are the design objectives in the design methodology (2). For this result, the proposed design methodology (1) derived the design solutions for demands more than 130 up to 180 [TEU/hour]. Moreover, for demands less than 120 [TEU/hour], the construction costs of the system designed with the use of the proposed design methodology (1) were lower than the construction costs of the system designed with the use of the design methodology (2).

From the result, we conclude that the upgrade and downgrade designs for lower and higher demands are necessary and important. Thus, the validity of the proposed design methodology was finally presented.

## VI. CONCLUSIONS AND FUTURE WORKS

### A. Conclusions

In this paper, for the realization of a highly efficient seaport container-handling system, we took into account the performance of the operating robots in addition to the number of robots. In order to solve a combinatorial design problem, we proposed a design methodology. By using this methodology, we designed the number of robots and their performance for the given demands. Finally, we presented the validity of the proposed methodology by comparing and evaluating construction costs of two systems, which were designed with the used of the proposed design methodology and a design methodology which does not take into account the robots performance. Moreover, we discussed the designed robots performance; then, we showed that a performance of an operation, which is a reason of the system bottleneck, was adequately designed.

### B. Future Works

In future works, we will take into account not only the four discrete performance values which were given as the design parameters but also continuous performance values.

## VII. ACKNOWLEDGMENTS

This research was partially supported by the Japanese Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 19760167, 2007–2008.

## REFERENCES

- [1] D. Steenken, S. Voss, and R. Stahlbock : "Container Terminal Operation and Operations research - A Classification and literature review," *OR Spectrum*, Vol. 26, No. 1, pp. 3–49, 2004.
- [2] H.-O. Günther and Kap Hwan Kim (Eds.) : "Container Terminals and Automated Transport Systems," *Springer-Verlag*, 2005.
- [3] S. Hoshino, J. Ota, A. Shinozaki, and H. Hashimoto : "Hybrid Design Methodology and Cost-effectiveness Evaluation of AGV Transportation Systems," *IEEE Transactions on Automation Science and Engineering*, in press.
- [4] S. Hoshino, J. Ota, A. Shinozaki, and H. Hashimoto : "Highly Efficient AGV Transportation System Management Using Agent Cooperation and Container Storage Planning," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2330–2335, 2005.
- [5] S. Hoshino, J. Ota, A. Shinozaki, and H. Hashimoto : "Design of an AGV Transportation System by Considering Management Model in an ACT," in *The 9th International Conference on Intelligent Autonomous Systems (IAS-9)*, pp. 505–514, 2006.
- [6] S. Hoshino, J. Ota, A. Shinozaki, and H. Hashimoto : "Improved Design Methodology for an Existing Automated Transportation System with AGVs in a Seaport Container Terminal," *Advanced Robotics*, Vol. 21, No. 3–4, pp. 371–394, 2007.
- [7] C.-I. Liu, H. Jula, and PA Ioannou : "Design, Simulation, and Evaluation of Automated Container Terminals," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 3, No. 1, pp. 12–26, 2002.
- [8] Gottwald Port Technology : "Automated Transport Systems for Container Terminals – Automated Guided Vehicles plus Software –," <http://www.gottwald.com/opencms/opencms/gottwald/index.html>
- [9] MITSUBISHI HEAVY INDUSTRIES, LTD. : "Advanced Technology Cargo Handling Systems," *Products Guide*, 2004.
- [10] S. Hoshino and J. Ota : "Integrated Design Methodology for an Automated Transportation System in a Seaport Terminal," *IEEE International Conference on Robotics and Automation*, pp. 858–863, 2007.
- [11] I.F.A. Vis and I. Harika : "Comparison of Vehicle Types at an Automated Container Terminal," *OR Spectrum*, Vol. 26, No. 1, pp. 117–143, 2004.
- [12] C.H. Yang, Y.S. Choi, and T.Y. Ha : "Simulation-based performance evaluation of transport vehicles at automated container terminals," *OR Spectrum*, Vol. 26, No. 2, pp. 149–170, 2004.