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Architectural Design of Terminal Operating System for a Container Terminal Based on a New Concept

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ABSTRACT

Automation ensures accurate and well-organized container transportation in container terminals. This paper addresses operational issues such as equipment scheduling and the coordination between various pieces of equipment in a rail-based automated container terminal. Containers are relayed using multiple types of equipment from road trucks to a vessel and vice versa. Therefore, handshaking is required during a container transfer between different pieces of equipment. Synchronization between the schedules of all the equipment is important to reduce equipment waiting times and the time required for transporting containers, which results in a short turnaround time for a vessel. This paper proposes an integrated control system with the objective of synchronizing the operations of different types of equipment, provides a list of decisions to be made by the control module of each type of equipment, and shows all the required information transfers between control modules. A scheme for the integrated scheduling of multiple types of equipment is proposed. The decisions made by each control module in a real-time fashion are listed with detailed explanations, and the information transfer between managers in a real-time situation at the proposed terminal is described.

Keywords: Automated Container Terminal, Terminal Operating System, Real-Time, Integrated Scheduling

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1. INTRODUCTION

The automation of container terminal operations has recently increased because of its ability to ensure accurate and high-performance operations. Operations in automated container terminals must be supported by the development of a terminal operating system (TOS). A TOS is used to make the required decisions for daily operations in a real-time fashion, while considering the current situations in the container terminal. The TOS provides suggestions for decision makers based on some rules or algorithms, which provide good solutions. This paper proposes a TOS design that includes integrated scheduling and various decision-making modules, related to many aspects of the container terminal operation.

Studies on TOSs have been conducted by Kim *et al.* (2004), Murty *et al.* (2005), and Michele and Patrizia (2014). Kim *et al.* (2004) introduced the architectural design of control software and a simulation-based testbed, in which various control rules were tested. The suggested control system consisted of a ship operation manager (SOM) and system controllers for automated guided vehicles (AGVs) and automated yard cranes (AYCs). A postponement strategy for dispatching decisions and a strategy for rearranging the sequence of AGVs were also proposed. Murty *et al.* (2005) described various interrelated decisions made during daily operations at a container terminal, with the goal of minimizing the berthing times of vessels, required resources, waiting times of equipment, and congestion inside the terminal. Some mathematical models and algorithms used in the decision support system design were discussed. Michele and Patrizia (2014) investigated the considerations required for the operating system choice in container terminals. Using a sample consisting of 65 European container terminals, all of the aspects that motivated the choice of one operating system over another were analyzed in order to discuss the important managerial and policy implications.

Various operations in container terminals are performed using many kinds of equipment. In order to synchronize all of the required equipment during container transportation in a terminal, an integrated scheduling approach is required. In this integrated scheduling approach, the effects of the decisions made for one piece of equipment on those for another need to be considered during the decision making. Otherwise, the decisions for more than one type of equipment need to be made simultaneously. Won and Kim (2009) introduced various planning activities in container terminals and identified decision-making problems in each planning activity. To integrate various planning activities, the concept of a resource profile and a simultaneous planning procedure were proposed, in which each resource's availability and requirements were considered during various planning processes.

An integrated scheduling problem, which considered the effects of scheduling decisions related to one piece of equipment on another piece of equipment in container terminals, was studied by Wang and Kim (2011). Wang and Kim (2011) proposed a quay crane (QC) scheduling algorithm that considers the workload of the yard cranes (YCs) in the container yard in order to reduce the congestion of YCs and yard trucks in a specific area of the storage yard, which are shared by multiple vessels.

Studies on the simultaneous scheduling of various kinds of equipment in container terminals have been done by Chen *et al.* (2007), Lau and Zhao (2008), He *et al.* (2015), and Kaveshgar and Huynh (2015). Chen *et al.* (2007) presented an integrated model to schedule QCs, YCs, and vehicles, while minimizing the total time to serve several ships. The problem was formulated as a hybrid flow shop scheduling problem with precedence and blocking constraints, and a tabu search algorithm was proposed to solve the problem. Lau and Zhao (2008) solved an integrated scheduling problem involving various pieces of handling equipment using a mixed-integer programming model. Two types of genetic algorithms were proposed: a multi-layer genetic algorithm and a genetic algorithm plus maximum matching. He *et al.* (2015) addressed the integrated scheduling problem for QCs, internal trucks, and YCs. A mixed integer programming model and an integrated simulation-based optimization, which integrated a genetic algorithm and particle swarm optimization algorithm, were developed to solve the problem. Kaveshgar and Huynh (2015) developed a mixed integer programming model and genetic algorithm combined with a greedy margin for simultaneously scheduling QCs and yard trucks. Real-world operational constraints such as the precedence relationships between containers, QC interference, and the safety margin were considered in the proposed model.

Various approaches to solve real-time problems in a container terminal have been studied by Lehmann *et al.* (2006), Petering *et al.* (2009), Park *et al.* (2010), and Choe *et al.* (2015). Lehmann *et al.* (2006) proposed three procedures to solve deadlock situations in an automated container terminal, in which direct or indirect requests between QCs, stacking cranes, and AGVs occur simultaneously. A matrix representation and graph-oriented method were introduced to detect the deadlocks. Petering *et al.* (2009) developed a real-time YC control system, in which some rules to select the next containers were proposed. A discrete event simulation model of a pure transshipment terminal was developed to evaluate the proposed system. Park *et al.* (2010) studied a real-time scheduling problem for twin rail-mounted gantry cranes and proposed heuristic-based and local-search-based methods, which rescheduled the cranes in real time for a given fixed-length look-ahead horizon. Choe *et al.* (2015) developed an online learning algorithm for dispatching AGVs, while considering changing situations in an automated container terminal. A preference function for selecting a job to be assigned was calculated, and the job selection decision was evaluated by running a simulation with a short look-ahead horizon.

This study is the first one, which proposes an architectural design of TOS for a new conceptual rail-based automated container terminal. In this terminal, transporters are moving on installed rails on the ground and above the yard. Transporters on the rails move faster than transporters used in traditional terminals. However, the restrictions to move on the rails cause inflexibility in the movements of the transporters. Therefore, appropriate methods to schedule and control the movements efficiently are necessary.

Another contribution of this paper is the complete overview of activities to be considered in TOS, including intra/inter remarshaling, re-handling, container relay operations, QC loading sequencing, network design, and deadlock checking during the movements of transporters or container transfer operations. In this paper, various operational issues related to numerous types of equipment in a container terminal are considered. Decisions are made by each manager in a real-time fashion, relationships between TOS functions are described, and various pieces of information are transferred between managers in order to provide accurate knowledge about the real situation in other parts of the terminal. In a real-time system, all of the decisions must be postponed to a moment as close as possible to the execution time of the corresponding actions in order to consider the real situation of the terminal. An integrated scheduling method is proposed to allow the synchronization of all of the equipment schedules.

2. CHARACTERISTICS OF CONSIDERED AUTOMATED CONTAINER TERMINAL

Figure 1 (top view) and Figure 2 (side view) show some new types of transporters used to transport containers in an automated container terminal based on a new concept. These are moving on the ground and above the yard. In the considered container terminal, the transporters that move on the ground (TG) travel throughout the rail network, between the QC and storage yard, whereas the transporters above the yard (TYs) can only move on a single vertical rail, on which they are mounted, as shown in Figure 1. The TG network consists of vertical and horizontal path segments, which connect transfer points below the QCs and TYs.

Each TG can move in horizontal or vertical directions throughout the TG network and requires a certain

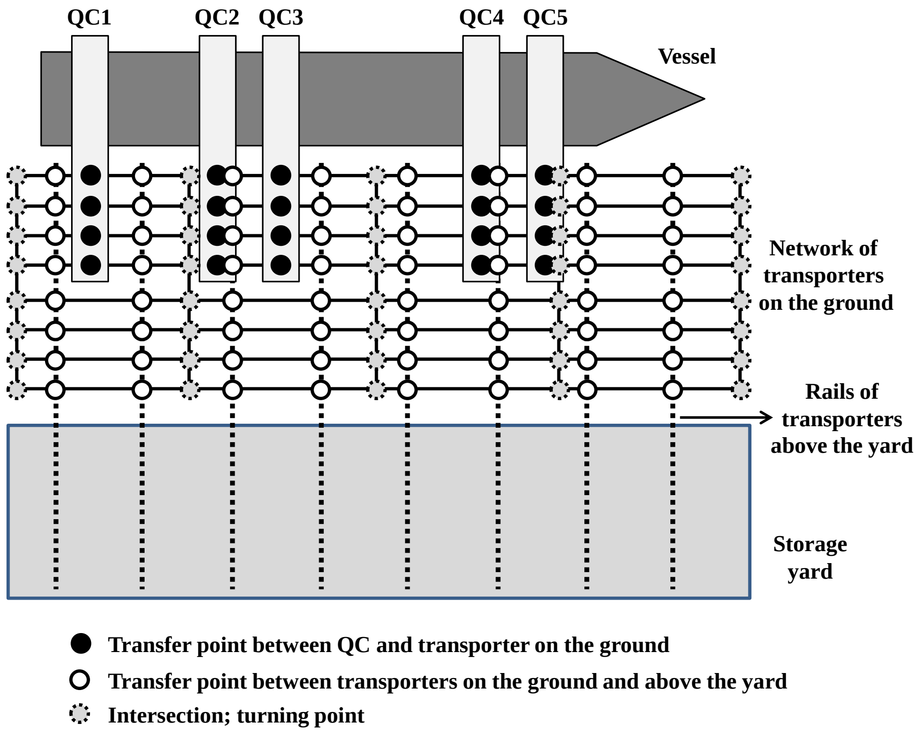

Figure 1. Illustration of rail-mounted transporter system, with installed rails on ground and above storage yard (top view).

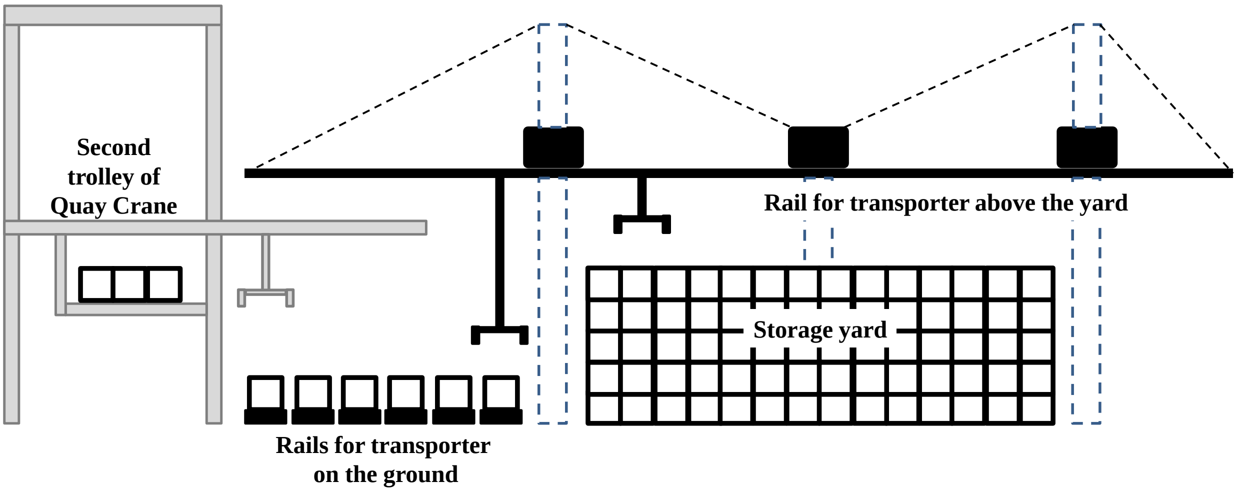

Figure 2. Illustration of rail-mounted transporter system, with installed rails on ground and above storage yard (side view).

turning time to change from a vertical to horizontal movement direction and vice versa. Two TYs are mounted on a single vertical rail above the storage yard and cannot pass each other.

Various orders are considered to be performed in the considered automated terminal, including loading, discharging, receiving, delivery, inter-remarshaling, and intra-remarshaling orders, and are related to the transportation operations for standard and refrigerated 20- and 40-ft containers. A loading order is performed as follows: a TY picks up a container from the storage yard, transports it to the TG transfer point (TP), and transfers it to a TG. The TG then transports the container to the QC TP and transfers it to a QC, which loads the container onto the vessel. A discharging operation is performed in the opposite way. A receiving order is described as an order to receive a container from an outside truck. This container will later be stored at the yard. A receiving order is performed as follows: an outside truck enters the gate and travels toward the TY TP. A TY picks up the container from the outside truck at the TY TP, and stores the container at the storage yard. A delivery order is performed in the opposite way.

A remarshaling order is used to relocate a container in order to reduce the required travel distance in the future. An intra-remarshaling order is used to relocate a container within the same vertical bay using TY(s) moving on a single vertical rail. The intra-remarshaling operation is performed for a loading container, which will be loaded on a vessel, or a carry-out container, which will be picked up from the storage yard using a TY and transferred from the TY to an outside truck. A container is included as a candidate for relocation in the intra-remarshaling operation based on the distance between its storage location and its designated TY TP. Because the estimated berthing times of the designated vessels for loading containers are known, only the loading containers of vessels that will soon berth are considered as candidate containers for the intra-remarshaling operation. The intra-remarshaling task is performed when the required TY is idle.

In an inter-remarshaling order, a container is transported from one storage bay to another storage bay, which requires a container transfer between a TG and TY. The loading and delivery containers are candidates for the inter-remarshaling operation, with considerations similar to the containers in the intra-remarshaling operation. However, an idle TG and two idle TYs are required to perform the inter-remarshaling operation. After selecting a container to be remarshaled in the inter-remarshaling operation, a destination TY vertical rail must be determined by considering the current workload of each TY vertical rail.

Each order is decomposed into several tasks based on the equipment required to perform the order. For example, as explained earlier in this section, a loading order must be performed using a TY, TG, and QC. Therefore, a loading order is divided into a TY task, TG task, and QC task. As a result of the decomposition, the tasks are then scheduled by each responsible manager, e.g., the TY and TG tasks are dispatched and scheduled by the TY and TG managers, respectively. Before performing a loading or delivery order, a re-handling task could occur, when the target container is located below another container in the storage yard.

3. SYSTEM ARCHITECTURE

3.1 Overall system Architecture

The proposed TOS consists of the planning system, managers, equipment, and database, as shown in Figure 3. All of the decisions are made in a real-time fashion, while utilizing the results of the berth allocation, QC scheduling, and load sequencing in the planning process. Each manager performs some functions, as listed in Table 1, which also include the movement and operation commands for the corresponding equipment. Further explanations of the important functions are given in Section 3.3.

In contrast with an automated container terminal, which uses AGVs to transport containers, the considered terminal uses TGs, which can only move on the installed rails. Because of the movement limitations, the considered terminal, which uses TGs, has less flexibility. In order to ensure operational flexibility, the operations of each piece of equipment must be well managed. Therefore, the yard manager is responsible to monitor and make decisions, which are related to the storage yard operations, while the TY and TG managers must schedule and monitor the movements of the TYs and TGs, respectively.

Additionally, some dynamic algorithms are developed to deal with the inflexibility in the TG network. Using these algorithms, decisions are made and modified continuously in order to make the best decisions, while considering the latest situations in the container terminal. Some of these algorithms are for flexible load sequencing, network design, and bidding-based dispatching. The flexible load sequencing method is used to determine which TG is allowed to enter important intersections before entering the QC TP during loading operations, while considering feasible slots on the vessel for loading the containers. The network design algorithm is used to determine the direction of each path segment in the TG network in order to minimize the travel time required by TGs. The directions are changed every time the QC position changes, and the required flows between nodes in the TG network change. Lastly, the bidding-based algorithm is used to dynamically dispatch TGs with the tasks, while continuously finding the best dispatching result with the minimum task delay and total travel times.

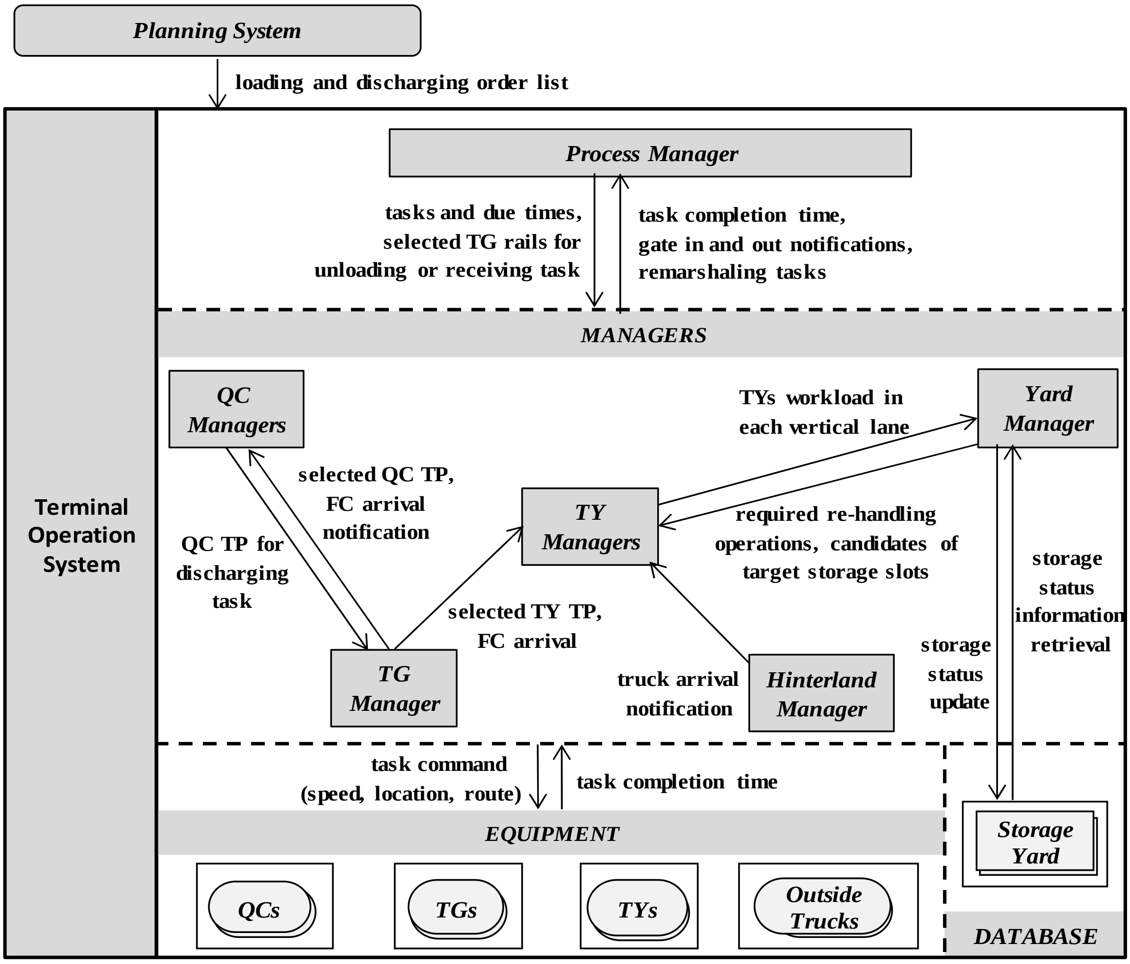

Figure 3. System architecture of terminal operating system.

Various information transfers are required before or after a manager performs a function or a piece of equipment starts or finishes performing a task. An information transfer acts as a triggering event or provides real-time information for a manager to perform a function, e.g., the TG manager performs the TG dispatching process after receiving a QC task completion notification from a QC manager, and a TY manager determines the storage location of a receiving container after receiving storage slot candidates from a yard manager. A manager transfers information to another manager in order to update the status of the corresponding equipment, e.g., a TG manager transfers information about the arrival of empty TGs at a TY TP to the TY manager in order to provide information about possible positions to release a loading container. Information is transferred from a manager to the corresponding equipment when a movement or operation command is given, e.g., the route and TG speed in each node of the route, which are transferred from the TG manager to a TG. Information is transferred from a piece of equipment to its manager when the equipment completes an operation or movement.

A sequence diagram is used to illustrate the functions and data transfers required to perform an order. An example of a sequence diagram of a loading order using TG(s) is shown in Figure 4. In the sequence diagram, before performing a function, a triggering event is started, and the required information is transferred to the responsible manager from another manager if necessary. Because all of the functions are performed in a real-time fashion, all the information required to perform a function are sent to the responsible manager right before the function is going to be performed in order to obtain the most updated information about the status of the equipment, utilization of the storage yard, and traffic in the TG network. When a piece of equipment needs to move or perform a container transfer operation, a command is given by the responsible manager to the equipment. This command includes detailed information such as the route for the equipment to travel and the required speed at each node during the travel, or the type of operation that must be performed. After the equipment completes the movement or container transfer, the responsible manager records the task completion information.

Table 1. Functions of each manager

Manager	Function
Process Manager	Loading, discharging, receiving, remarshaling, and delivery tasks generation and due time determination
	Rescheduling related task because of a task delay
QC Manager	Next QC (loading/unloading) task selection
	QC TP selection (for QC movement)
TG Manager	TG dispatching
	TG TP determination
	TG network design (determination of path segments' directions)
	TG (empty and loaded) routing
	Idle TGs parking location determination
	Cyclic deadlock prevention among TGs by allocated task exchange or TG rerouting
	Deadlock resolution among different types of equipment
TY Manager	Next TY task selection
	TY scheduling, including collision avoidance (using a single TY)
	TY relay operation scheduling (using two TYs on the same rail)
	Deadlock resolution caused by mismatch between TG and TY (allocating task exchange to TYs)
	TY re-handling task generation and due time determination
	Specific storage location determination
Yard Manager	Candidate of specific storage location determination for discharging, receiving, and remarshaling containers
	Storage bay determination for receiving, discharging, and remarshaling
	Remaining duration of stay checking for containers to be remarshaled
Hinterland Operation Manager	Yard congestion checking
	TP determination
	Truck routing

Information about the completion of tasks is always provided to the process manager in order to evaluate the execution of the planned schedules and perform any necessary rescheduling, while the result of a function is transferred by the responsible manager to another manager if it is required to perform another function. For example, in order to perform a receiving order, the target TY vertical rail is determined by the yard manager. The information required to determine the target TY vertical rail includes the workloads of the TYs in each TY vertical rail and the current information about the containers stored in the storage yard. The information about the workloads of the TYs in each TY vertical rail must be obtained from the TY manager. Therefore, the yard manager requests this information from the TY manager after an outside truck enters the gate. Then, the TY manager obtains information about the workloads of the TYs and sends this information to the yard manager, who then determines the designated TY vertical rail where the container will be stored.

In the proposed system, decisions are made while considering the latest information representing real-time situations in the container terminal. The information must always be updated after any function is performed by a manager (e.g., the selected QC TP), which is required by the TG dispatching and TG loaded routing functions. This information must be updated by the TG manager during the loading operation. In the TG dispatching function, QC and TY TPs are required to calculate the required travel time of the flatcar dispatched for each task, and assess the feasibility of the dispatching, while in the TG loaded routing function, the QC TP is required as the destination of the TG. These functions are performed at different times. The TG dispatching function is performed every time a QC completes an unloading or a loading task, whereas the TG loaded routing function is performed later, after the TG receives the loading container and starts its loaded travel. The selected QC TP must be continuously updated in order to consider real-time situations during the execution of each function.

3.2 Functions of Process Manager

3.2.1 Integrated Scheduling Function

Generally, more than one piece of equipment must be used to perform an order. For example, to perform a loading order, a container is picked up by a TY from the storage yard, and transferred to a TG, which will transport the container to the QC. Finally, the QC loads the container onto the vessel.

The dispatching and scheduling processes of each

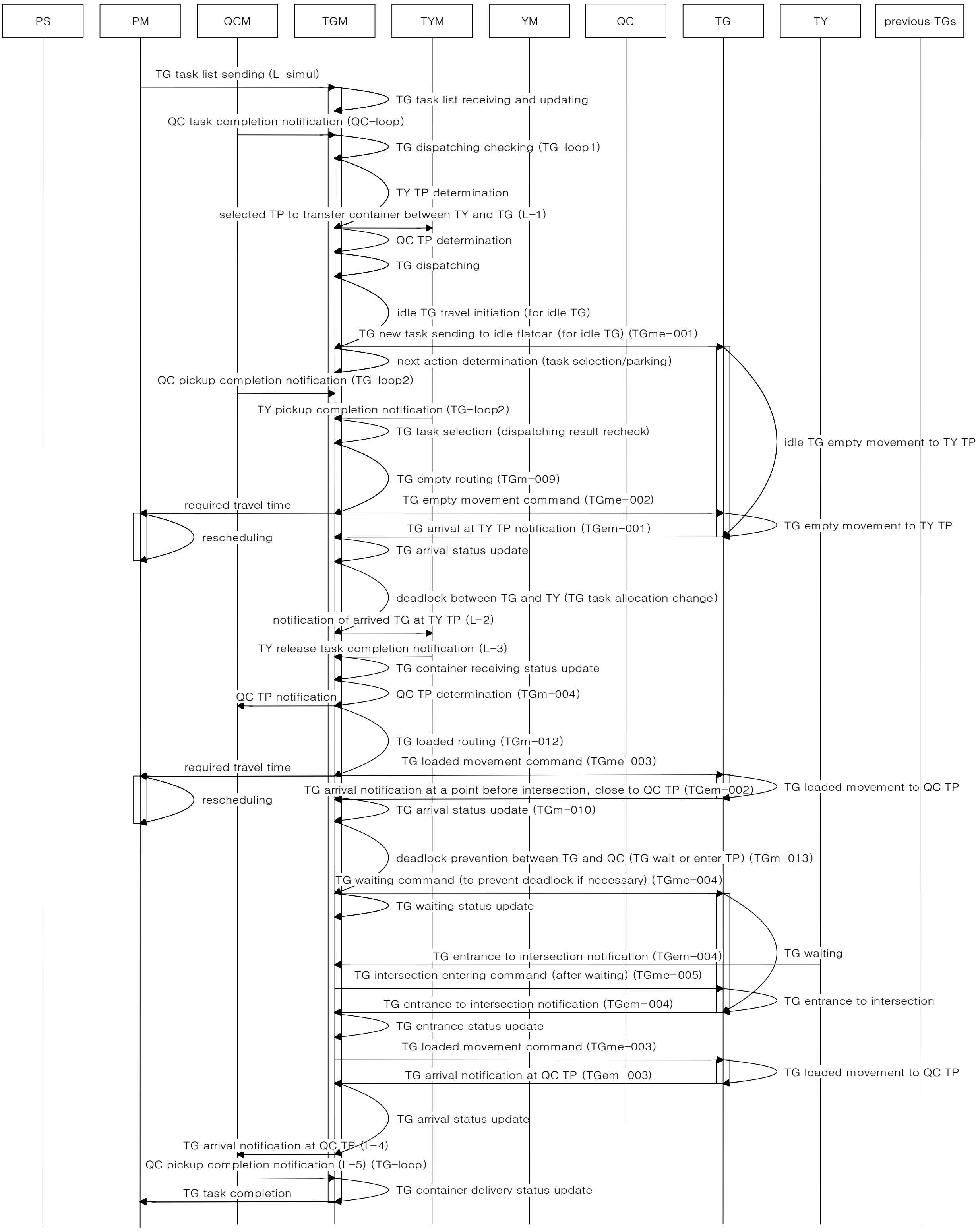

Figure 4. Sequence diagram for TG manager during the execution of loading order.

type of equipment are performed by separate managers. Each loading or discharging order must be performed before a due time, which is determined by the process manager, whereas a receiving, delivery, intra-remarshaling, or inter-remarshaling order is started after its triggering event. The receiving and delivery orders are triggered by the entrance of a truck at the gate, while remarshaling orders are triggered by the idle states of transporters above the yard and on the ground.

Because an order is performed using multiple pieces of equipment, several handshaking operations between the equipment are required. Therefore, good equipment coordination is important to avoid equipment waiting time during the handshaking process. If each manager only aims to optimize the operation of their own equipment, without considering the schedules of other equipment, a long waiting time for the other equipment, which is transporting the container to be transferred, and a late task completion time will occur. In order to avoid these, an integrated scheduling function is performed by the process manager.

In the integrated scheduling function, the due time of each order or the triggering event time is set as the basis to determine the due time of each task performed by each required piece of equipment, which is determined by considering the estimated operational time of the related equipment. Then, the calculated due times are used as the basis for the scheduling by each manager. By performing integrated scheduling, the schedules of all the equipment can be effectively synchronized.

3.2.1 Rescheduling Function

The completion of a task by any piece of equipment can be delayed for several reasons such as equipment breakdown or unpredicted traffic, which causes the late arrival of transporters and a waiting time for other pieces of equipment during the container transfer. Any delay of a task completion is recorded by the equipment's manager and reported to the process manager. The process manager then revises the due time of the not-yet-performed tasks to transport the same container if the changes in the due times are assumed to be significant enough to be considered, as measured by a predetermined threshold. The related managers are informed of the revised due times, which allows them to reschedule the tasks with the modified due times.

3.3 Functions of Other Managers

The QC, TG, TY, and hinterland operation managers mainly perform dispatching and schedule the operations of the equipment needed to transport all the containers while satisfying the due times that have been determined by the process manager. The yard manager aims to determine the required storage locations for all the containers in the terminal. All of the detailed functions of each manager are listed in Table1.

The TG manager is responsible for determining the QC or TY TPs, where the containers will be transferred between a QC and TG, or a TY and TG, respectively. In the considered layout, the TG network is considered to be the bottleneck of the terminal because there are many TPs in this network where TGs need to remain during the container transfer processes, while simultaneously, many TGs are travelling throughout the TG network. In order to optimize the movements of TGs in the TG network, the QC and TY TPs are determined by the TG manager, who later informs the QC, TY, and hinterland managers. In order to make the flow control of the TGs easier, the TG manager determines the directions of unidirected vertical and horizontal path segments, while aiming to minimize the total required travel time of the TGs.

In the terminal, multiple TGs are moving simultaneously in the same TG network. The movement of a TG can be restricted by the movements of other TGs in the network. Similarly, the movement of a TY can be restricted by the movement of another TY on the same vertical rail above a storage bay. Therefore, the TG and TY managers must perform traffic control functions such as collision detection between pieces of equipment during their movements, parking location determination for idle equipment, and deadlock prevention or resolution functions to prevent TGs from waiting at certain nodes in the network.

The TG and TY managers perform collision detection between the TGs or TYs during the TG or TY routing process, respectively. When a new route is made, the previously determined routes and already reserved times in each node in the network are considered. Because the positions of idle TGs in the TG network or an idle TY on a vertical rail can interfere with the movement of another TG or TY, respectively, the TG and TY managers must determine the parking locations for idle equipment while avoiding the flow of TGs and TYs.

During the movements of TGs, a circular deadlock can occur, as illustrated in Figure 5. In a circular deadlock, some TGs are located in a circular form, and based on its route, each TG must enter a position that is occupied by another TG. The TG manager can prevent a circular deadlock by continuously checking whether or not the entrance of a TG into an intersection in the TG network will cause a circular deadlock.

The TG and TY managers are also responsible for solving any deadlocks that occur during the container

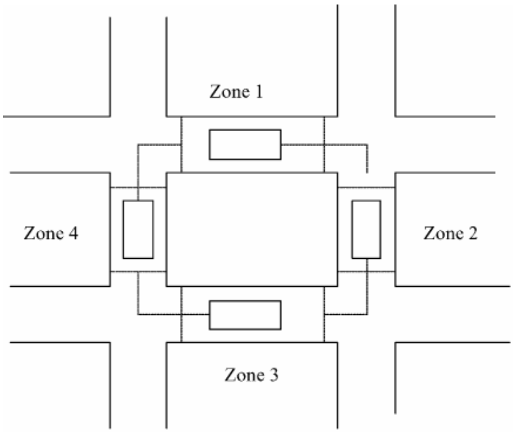

Figure 5. Cyclic deadlock in TG network (Moorthy *et al.*, 2003).

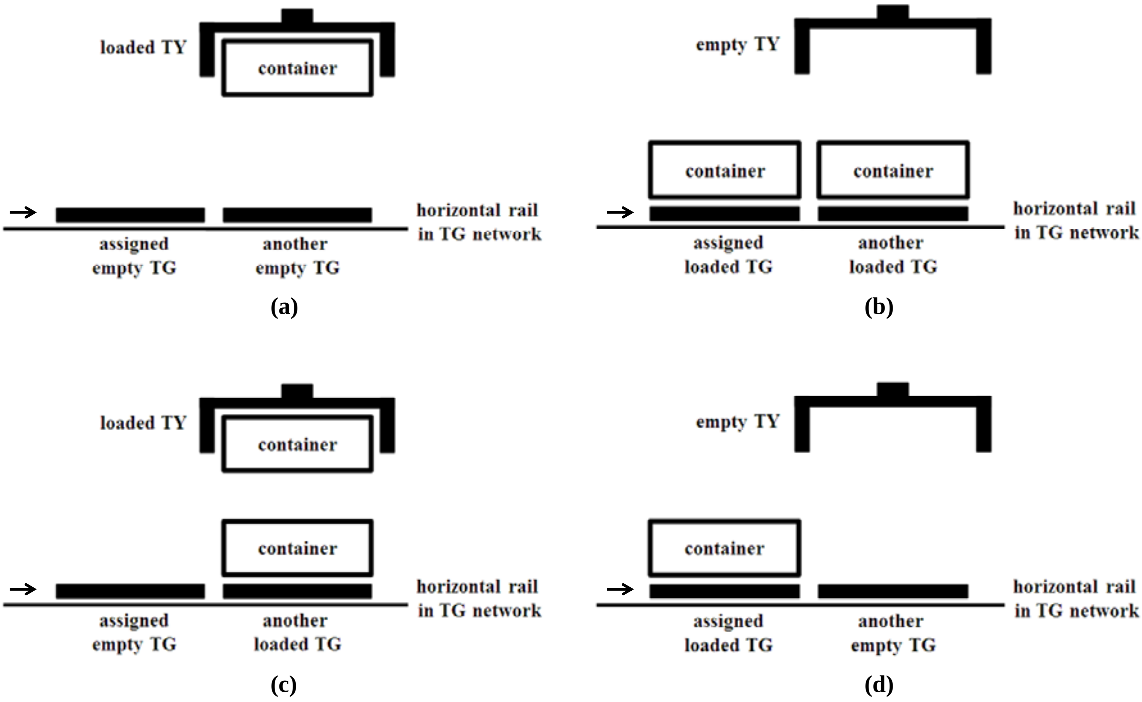

Figure 6. Deadlock during container transfer between TG and TY.

transfer between a TG and TY. These deadlocks occur because the arrival order of a TG at a TY TP is changed from the plan as a result of uncertain traffic in the TG network. The deadlocks are differentiated based on the empty and loaded states of the TG and TY, as shown in Figure 6. In Figure 6(a), a loaded TY must release the container to the assigned empty TG, but another empty TG arrives earlier at the TY TP. To solve this deadlock, the TG manager exchanges the TG dispatching results between the assigned empty TG and another empty TG. Thus, the loaded TY can release the container to the TG that arrives empty. In Figure 6(b), an empty TY must pick up a container from the assigned loaded TG, but another loaded TG arrives first at the TY TP. The TY manager solves the deadlock by changing the order of TY tasks in their task list and letting the empty TY pick up the container from the loaded TG that arrived first. In Figure 6(c), a loaded TY cannot release its container because another loaded TG arrived earlier at the TY TP. The TY manager solves the deadlock by adding a TY task to release the currently being carried container to a temporary slot in the storage bay, adding another TY task to pick up the container from the TG that arrived loaded, and delaying the TY task to release the initial container to the next assigned empty TG. In Figure 6(d), an empty TG arrives earlier at a TY TP, while an empty TY is scheduled to pick up a container from a loaded TG. To solve this deadlock, the TY manager exchanges the TY task orders in the TY task list, which allows the TG that arrived empty to pick up the container to be released.

When a discharging container will be stored in the yard, two decisions must be made about the target storage bay and specific target slot within the selected storage bay. The storage locations are determined based on coordination between the yard and TY managers. The yard manager finds a storage bay that is located below the TY vertical rail with the least workload among all the vertical rails. The TY workload information for each vertical rail is obtained from the individual TY managers.

Later, after a TY picks up a discharging or receiving container, the specific storage slot within the selected storage bay is determined by the corresponding TY manager. Before determining the storage slot, the TY manager requests a list of storage slot candidates from the yard manager. Then, the TY manager determines the target storage slot that can be accessed while avoiding collisions with another TY in the same vertical rail.

4. REQUIRED CONSIDERATIONS TO IMPLEMENT SYSTEM

During the operation of a container terminal, the vessel berthing time must be minimized. Therefore, algorithms that can reduce the total required container handling times must be implemented. These algorithms must also utilize little computational time because the decisions are made in a real-time fashion.

Various tasks can be performed earlier or later than the plans. Therefore, monitoring and control functions must also be embedded into the system in order to continuously check the status of the equipment and storage yard, as well as detect unpredicted situations and deal with them immediately.

Emergency situations, e.g., equipment breakdown, could occur and disturb the flow in the terminal. In order to effectively handle an equipment breakdown, maintenance procedures must be well designed. In the automated container terminal, the entrance of people into the terminal is limited for safety reasons. Therefore, if possible, the maintenance must be performed using the equipment available in the terminal, e.g., using an idle TG to transport a broken TG to the maintenance area. The algorithms that are normally used to perform container transportation can be used to dispatch and schedule the movement of maintenance equipment.

The proposed architecture system, including various algorithms and the integrated system are being implemented in a simulation model. In the simulation model, information transfers between functions in the system are tested, and performances of the TOS are measured, including the total ship berthing time, the total vehicle operation and waiting times, and the number of QC moves per hour. Performance tests are being performed by using a real-sized terminal in which 2-3 ships can be berthed at the same time. Uncertain QC operational times, storage yard equipment operational times, and vehicle travel times are also considered in the simulation in order to test the proposed handling system based on realistic data on container flows within the terminal.

The handling system assumed in this study consists of transport system, storage system, and QC system. The two most popular handling systems for automated terminals are as follows: the system consisting of automated perpendicular YC system, AGV system, and QC system, which is popular in European countries; the system consisting of semi-automated parallel YC system, manually operated truck system, and QC system, which is popular in Asian countries. Both systems consist of transport system, storage YC system, and QC system, which is the same structure as the handling system proposed in this study. Thus, most of the modules, the functions of each module, data bases, and information transfer protocols, which are proposed in this study, may be applied to most of automated container terminals currently in operation.

Development of the system architecture, the functions of each module, data bases, data transfers between modules in this study are preliminary results, which may be used for the development of a real TOS. User interfaces for decision-making for each function, explained in Table 1, may be used for the real TOS. Decision results made by each manager will be stored in a database and transferred to another manager by using provided information transfer protocol, which are explained in Figure 3 and Figure 4.

5. CONCLUSIONS AND FUTURE RESEARCH

This paper addressed the various decisions that must be made by individual managers in a rail-based automated container terminal. The types of information that must be transferred for decision making were also listed. In order to synchronize the movements of many types of equipment, a due time setting method was proposed, which leads to a reduction in the total berthing time of a vessel. A due time recalculation method was proposed as a response to unpredicted events that occur during the operation.

The proposed system architecture, including all required functions and data transfers, is a preliminary design of a terminal operating system (TOS) for a real implementation of the proposed handling system. Each proposed function may be used as a guideline to select appropriate algorithms, which can be implemented to solve real-operational decision-making problems in the terminal and to determine required databases for storing decision-making results, and to design required data transfer procedures. Note that the handling system in this study consists of transport system, storage system, and quay crane system, which is the most popular type in practice. Thus, the design of software proposed in this paper can be applied to the development of TOSs for other types of automated container terminals after minor modifications.

More detailed studies on the fast real-time algorithms that are required to solve the problems of each manager in the container terminal must be conducted. The input data, decision variables, objectives, and constraints must also be clearly stated. Given that the TG network plays an important role in container transportation between the quay and yard sides in a container terminal, problems related to the TGs must be well defined, including the transporter's traffic control using deadlock prevention or resolution methods, rerouting procedures to avoid long waiting times for TGs at TPs, and deadlock prevention during a TG's travel toward the loading QC.

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