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An integrated framework for various operation plans in container terminals

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ABSTRACT

This study provides a framework for integrating various planning activities in container terminals. First, we introduce various planning activities in container terminals and identify decision-making problems for each planning activity. Input parameters, decision variables, objectives, constraints, time buckets, and the planning horizon for each decision activity are identified. Next, we introduce the concept of a resource profile and planning procedure simultaneously by considering availabilities of various resources and resource requirements in a planning activity.

Keywords: container terminals; planning; resource capacity

INTRODUCTION

Port container terminals are located at places where containers are transshipped from a transportation mode to another. Their main functions are to provide transfer facilities for containers between vessels and land transportation modes, such as trucks and trains. They are characterized by highly complex systems that involve numerous pieces of equipments, operations, and handling steps. Operations in container terminals can be classified into a vessel operation process during which containers are discharged from and loaded onto a vessel and receiving and delivery operation processes during which containers are transferred from and to external trucks. During these operations, assigning resources to these operations and scheduling these operations become major planning issues in container terminals.

Many researchers reviewed planning problems in an operation of container terminals (Ramani, 1996; Bontempi *et al*., 1997; Meersmans and Dekker, 2001; Vis and de Koster, 2003; Steenken *et al*., 2004; Murty *et al*., 2005; Crainic and Kim, 2007). Ramani (1996) divided the basic task in the management of container terminals into a berth allocation, yard planning, stowage planning, and logistics planning in container operations. A berth allocation issue is to plan which berth is to be assigned to a given ship for loading and unloading its containers. A yard planning involves the allocation of storage spaces to import, export, and transshipment containers. A stowage planning assigns stowage locations to outbound containers in bays of a ship. A logistic planning deals with scheduling and coordinating the operation of port equipments, such as quay cranes, prime movers, and yard cranes for moving containers among different sources and destinations (for example, gates, vessels, rail stations, storage yards, and container freight stations).

Bontempi *et al*. (1997) assigned a different time horizon to each planning problem in container operations. They used the solution obtained in long-term problems (container storage policies) as an input for mid-term problems (resource allocation problems) and the solution obtained in mid-term problems (resource allocation policies) as an input for short-term problems (load and unload scheduling problems). Meersmans and Dekker (2001) and Vis and de Koster (2003) distinguished decisions on container handling operations into strategic, tactical, and operational levels according to the time horizon involved. A time horizon in decisions for the strategic, tactical, and operational level covers one to several years, a day to months, and a day, respectively.

Steenken *et al*. (2004) reviewed terminal logistics and optimization methods. They described the important processes in container terminals that can be optimized by means of operations research methods: ship planning processes (consisting of berth allocation, stowage planning, and crane split), storage and stacking logistics, transport optimization, and simulation systems. Murty *et al*. (2005) introduced nine decisions to be made in daily operations: allocation of berths to arriving vessels, allocation of quay cranes to docked vessels, appointment of arrival times to external trucks, routing of trucks, dispatch policy for trucks at terminal gatehouses and docks, storage space assignment, yard crane deployment, internal truck allocation to quay crane, and optimal internal truck hiring plans. Günther and Kim (2006) divided planning and control levels in container terminals into three categories:

terminal design, operative planning, and real-time control. A terminal design level contains multi-modal interfaces, terminal layout, equipment selection, berthing capacity, and IT-system and control software. An operative planning level contains storage and stacking policies, crane assignment and split, berth allocation, and stowage planning. A real-time control level contains landside transport, quayside transport, slot assignment, and crane scheduling operation sequencing. Crainic and Kim (2007) introduced models for the operational planning control in container terminals. Their models include scheduling of berths, scheduling of quay cranes, stowage planning and sequencing, storage activities in a yard, and allocation and dispatching of yard cranes and transporters.

This study provides a framework for integrating various planning activities in container terminals. First, we introduce planning problems in container terminals and identify a decision activity for each planning problem. Input parameters, decision variables, time buckets, and the planning horizon for each decision activity are identified. Next, we introduce the concept of a resource profile and planning procedure simultaneously by considering resource capacities and resource requirements.

Section 2 provides a framework for the operation planning process in container terminals. Section 3 discusses resource profiles for certain decision activities related to various operational plans. Three subsections illustrate examples of the capacity planning in berth planning, scheduling of quay cranes, and yard planning, respectively. Finally, Section 4 presents a conclusion.

FRAMEWORK FOR A PLANNING PROCEDURE

Container terminals perform various handling operations by utilizing such resources as quays or berths, quay cranes (QCs), storage yards (SYs), yard cranes (YCs), traveling areas (TAs), and transporters (TRs). A traveling area represents a traffic zone or a set of transfers for trucks. Two most important performance measures in a container terminal are turnaround time of a vessel and road trucks in a terminal. Turnaround time of a vessel and road truck highly depends on the capacity of applied resources and methods to allocate the capacity of resources in handling tasks. This section describes how the capacity of resources can be explicitly considered during each of planning processes and information on the capacity can be shared among different planning processes in container terminals.

Resource capacities are represented as follows: the capacity of berths can be represented as the product of one dimensional space (usually length) and time. The capacity of QCs, TRs, and YCs are measured in QC times, TR times, and YC times, respectively. If all QCs have the same capacity, we can evaluate the capacity of QCs by multiplying the number of QCs by their available time. In a similar way, the capacity of other resources can be evaluated. Tab. 1 summarizes units to represent the capacity of each different type of resources.

Tab. 1. *Resources and units*

Resources	Units
Berth (H)	Length of the berth × berthing duration
QC (C)	Number of QCs × operation time
TR (R)	Number of TRs × operation time
YC (Y)	Number of YCs × operation time
TA (A)	Number of TRs passing the TA × operation time
SY (S)	Number of slots (in TEU) × storage duration

All planning activities for operations must check the availability of resources required for the operations. An amount of resources required for an operation can be estimated as follows: berthing a vessel requires the resource of berths based on the length of a vessel multiplied by the occupation time. Unloading or loading containers consume the resource of QCs by the number of containers multiplied by the standard handling time per container. The workload in unloading and loading operations on TRs can be evaluated by multiplying the number of containers with the average transportation time per container including empty travels. The workload of unloading and loading operations on YCs can be calculated by multiplying the number of containers with the standard handling time of a YC per container. The workload on TAs represents the expected future occupation of TAs by TRs. The storage space of a SY requires a certain amount of reservation before the storage of containers and actual occupation by containers. Fig. 1 shows a planning procedure in container terminals. We classified this procedure as long-term, mid-term, and short-term according to the planning horizon.

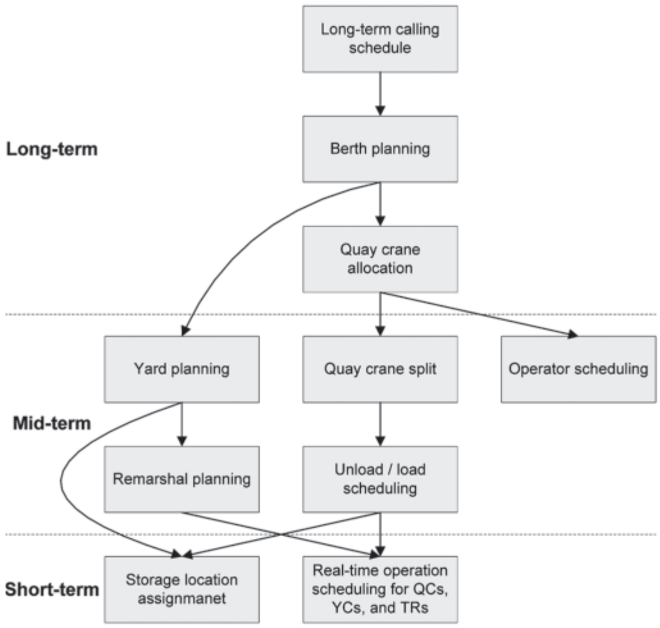

Fig. 1. *Framework of the planning process*

Every planning process must consider the availability of related resources. Fig. 2 shows several key planning processes and their related resources that must be checked before commitment. The berth planning is a decision process on the berthing location and time for ships. A certain zone in a berth is assigned to a ship for loading and unloading containers for a certain period of time. Scheduling of QC works (split) is a decision process on a service sequence of bays in a ship by each QC and time schedule for services. Several QCs are usually assigned to one ship. Yard planning is a decision process on storage locations for containers during unloading operation, receiving operation, and remarshalling operation. Scheduling of unloading is a decision process on a work sequence and time for inbound containers that are discharged from a ship to storage locations in a SY. Scheduling of loading is a decision process on a work sequence and time for outbound containers that are loaded from a SY to storage locations in a ship. Remarshal planning is a decision process on movements of containers from a storage block to another and time of movements.

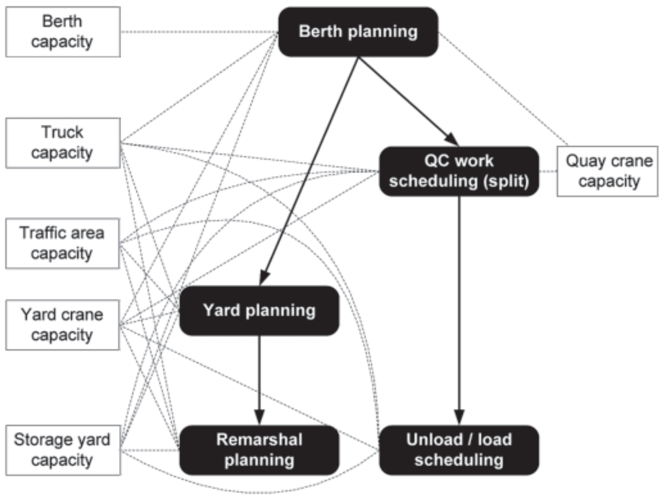

Fig. 2. *Various operational plans and their related resources*

Decisions to be made by each planning process are summarized in Tab. 2. The first line of each planning process represents the activity or activity unit on which a decision will be made. The second line represents the reference moment of the activity from which the time-phased consumption of resources resulting from the decision will be estimated. The third line represents contents of the decision to be made by each planning process.

The following sections will discuss the resource profile in major decision processes for long-term and mid-term plans in container terminals: berth planning, scheduling of QC works, and yard planning. This study considers six resources: berths, QCs, TRs, YCs, TAs, and SY. The operation time applied in resources is configured as berthing time, handling time by QCs, transportation time by TRs, handling time by YCs, occupation time of TAs, and storage time of SY. For describing the resource profile and plan, the following notations are used:

Tab. 2. *Contents of the decision for various operational plans*

Long-term	
Berth planning (B)	
Activity to be planned	Berthing of each vessel
Reference moment of the activity	Beginning of the berthing
Contents of the decision	Berthing position and time of each vessel
Mid-term	
QC work scheduling (Q)	
Activity to be planned	Loading or unloading task on deck or in hold of a bay by a QC
Reference moment of the activity	Beginning of each task
Contents of the decision	Schedule for QCs to discharge (or load) containers from (or onto) vessels
Yard planning (P)	
Activity to be planned	Receiving outbound containers for a vessel or unloading inbound containers by a QC for a vessel for a period
Reference moment of the activity	Starting of arrivals of outbound containers at a gate or unloading of inbound containers from a vessel
Contents of the decision	Storage positions for outbound containers for a vessel arriving during a period or inbound containers discharged from a vessel
Remarshal planning (M)	
Activity to be planned	Moving a set of containers from a block to another for a period
Reference moment of the activity	Starting of movements
Contents of the decision	Containers to be moved and their sources and destination positions for a period
Short-term	
Unload scheduling (U)	
Activity to be planned	Unloading containers on deck or in hold of a bay
Reference moment of the activity	Starting of unloading
Contents of the decision	Discharging sequence of individual inbound containers
Load scheduling (L)	
Activity to be planned	Loading containers onto deck or into hold of a bay
Reference moment of the activity	Starting of loading
Contents of the decision	Loading sequence of individual outbound containers

Indices

r – index used in resources where r = H (berth), C (QC), R (TR), Y (YC), A (TA), and S (SY)
t – index used in periods where t = 1, 2, …, m
a – index used in activities where a = 1, 2, …, n.

Problem data

s_{ar}^{t} – a unit amount of resource **r** that must be used with the time offset of **t** for carrying out activity **a**. In a berth planning, for example, if a vessel is decided to berth at a quay at period p (let this be activity "B"), the operation time of QCs at period (p + t) will be required by the amount of s_{BC}^{t}.

Sets

T_{ar} – a set of time offsets in which resource r is consumed by activity **a**
B – a set of activities related to berth plans. Each activity corresponds to a decision on the berthing of a vessel
Q – a set of activities related to QC work schedules. Each activity corresponds to a decision on the work for a vessel by a QC
P – a set of activities related to yard plans.

Decision variables

X_a – a decision vector for activity **a**. As an illustration, a decision vector in a yard plan for outbound containers is a set of storage blocks for the arriving outbound containers to be stacked and the amount of containers to be stored at each storage block.

BERTH PLANNING

A berth planning determines the berthing position and time of a vessel. Tab. 3 shows input parameters, decision variables, objectives, and constraints for the berth planning. A berth planning requires such input data as a calling schedule, favorable berthing location, length of a vessel, required draft of each vessel, required unloading and loading time for each vessel, and various constraints and priorities for locating and sequencing a vessel. One of the objective in a berth planning is to locate vessels at the most favorable position on the quay that will reduce the container delivery time between the marshaling yard and QCs and also to make vessels to depart the port before their committed due times. Also, the waiting time of vessels at a port must be minimized.

Tab. 3. *Definition of problems in a berth planning*

Input parameters	Calling schedule of vessels Favorable berthing location of each vessel Length of each vessel Draft required for each vessel Number of unloading and loading containers of each vessel Resource profiles
Decision variables	Berthing position of each vessel Berth time of each vessel
Objectives	To minimize delays in the departure of a vessel To minimize the travel distance between the shore and the yard for all containers in a vessel To minimize the waiting time of a vessel at a port
Constraints	Depth of water for berths Arrival time of a vessel at a port Availability of resources

Resource requirements depend on the number of unloading and loading containers and are evaluated by using the load profile of each resource in a berth planning. The requirement of each resource can be determined as a time-phased way with respect to the berth time of a vessel. Decision variables in a berth planning consist of the berthing position and berthing time of each vessel. By adding the schedule of a vessel in a berth plan, various resources are required as shown in Figs 3-(a) and (b). Figs 3-(a) and (b) show the resource profile for outbound and inbound flows, respectively.

A resource profile can be evaluated by using several different ways: s_{BH}^{0} indicates the amount of berths required in the berth plan B at a day when a vessel arrives at a berth. It can be evaluated by using (the length of a vessel plus the allowance between adjacent vessels) × (the expected berthing duration of a vessel). s_{BC}^{0} can be evaluated by using {(the time for a QC to transfer an outbound container to a slot of a vessel) × (the percentage of loading containers among all containers for a vessel) + (the time for a QC to transfer an inbound container to a TR) × (the percentage of unloading containers among all containers for the vessel)}. Standard time that includes not only pure operation time but also unavoidable delays and personal and fatigue allowances must be used.

Because TRs are required for loading and unloading operations, s_{BR}^{0} can be evaluated in the similar way as s_{BC}^{0}. s_{BY}^{t} for t < 0 can be evaluated by using (the time for a YC to receive an outbound container from an external road truck) × (the percentage of containers, among all the outbound containers, arriving at a SY on the tth day before the berthing of a vessel). s_{BY}^{t} for t > 0 can be evaluated by using (the time for a YC to transfer an inbound container to an external road truck) × (the percentage of containers, among all the inbound containers, leaving a terminal on the tth day after the departure of a vessel). s_{BY}^{t} for t = 0 can be evaluated by using {(the time for a YC to transfer an outbound container to a TR) × (the percentage of loading containers among all containers for a vessel) + (the time for a YC to receive an inbound container from a TR) × (the percentage of unloading containers among all containers for a vessel)}. s_{BS}^{t} for t ≤ 0 can be evaluated by using (the cumulative percentage of containers, among all the outbound containers, having arrived at a SY until the tth day before the arrival of a vessel) × (the length of a period). s_{BS}^{t} for t ≥ 0 can be evaluated by using {(1 – the cumulative percentage of containers, among all the inbound containers, having left the terminal until the (t – 1)th day after the departure of a vessel) × (the length of a period)}.

As an example, we illustrate how s_{BY}^{t} for t < 0 can be estimated as follows. In order to evaluate s_{BY}^{t} for t < 0, we must have the following two data: the operation time for a YC to receive an outbound container from an external truck; and the percentage of containers, among all the outbound containers, arriving at a SY on the tth day before the arrival of the vessel. Tab. 4 shows an example of s_{BY}^{t}, for t < 0. The expected handling time for a receiving operation by a YC used in the example is 1.521 minutes.

Tab. 4. *Example of s_{BY}^{t}, for t < 0*

t (day)	-6	-5	-4	-3	-2	-1
Percentage of containers [%]	2	5	6	10	12	65
s_{BY}^{t} (minutes)	0.030	0.076	0.091	0.152	0.183	0.989

Tab. 5 summarizes the data used for calculating a resource profile. Tabs 4 and 6 show the percentage of containers arrived at a SY on the days before loading and of containers left the terminal on each day after the departure of a vessel, respectively. Tab. 7 illustrates the resource profile for berthing of a vessel.

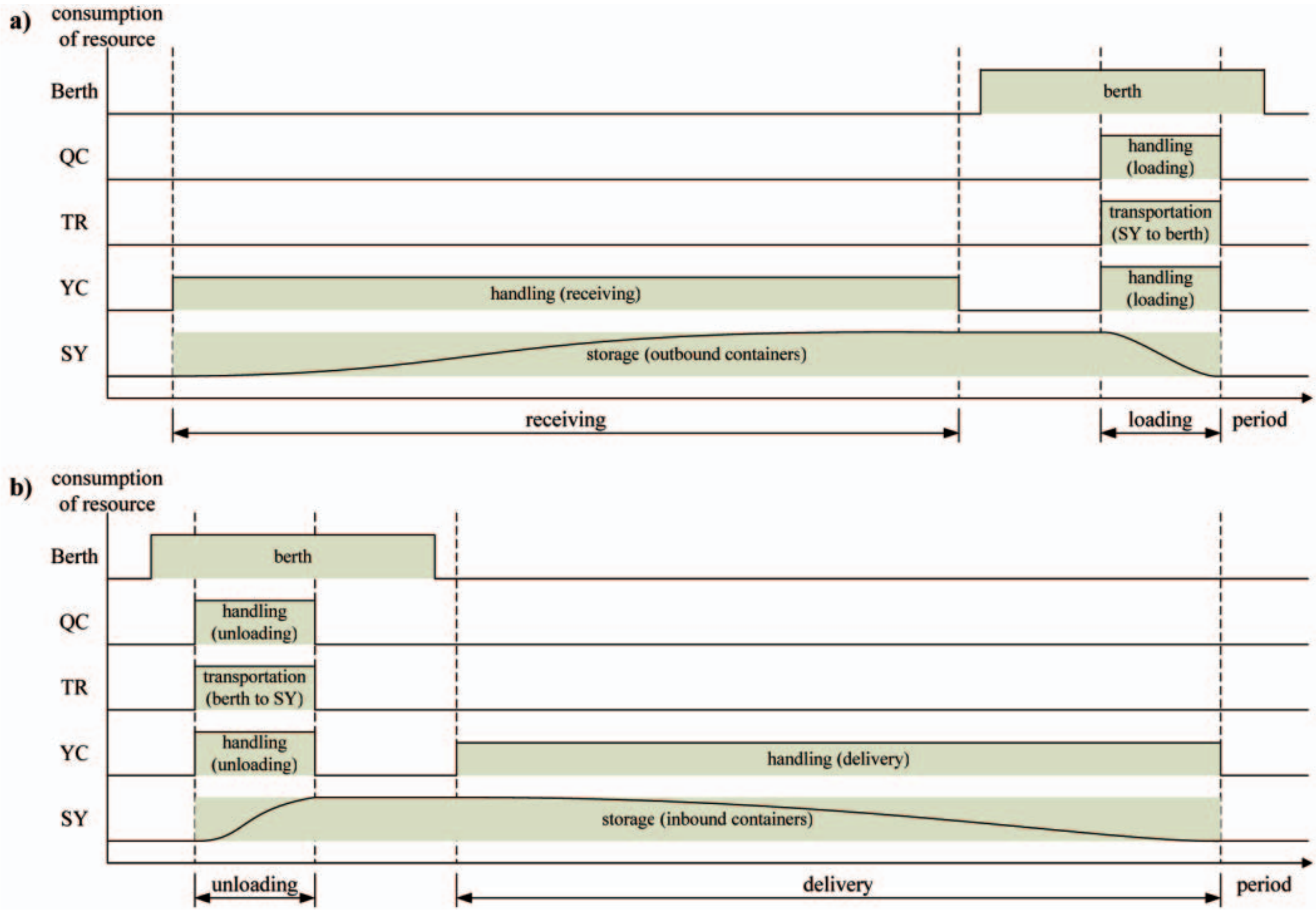

***Fig. 3.** Resource profile for berthing a vessel. **a)** resource profile for outbound containers, **b)** resource profile for inbound containers*

***Tab. 5.** Data used for calculating the resource profile for a vessel in a berth planning*

Length of the vessel plus the allowance between adjacent vessels	300 m
Berthing duration of the vessel	18 hrs
Number of loading containers for the vessel	540
Number of unloading containers for the vessel	560
Time for a QC to transfer an outbound container to a slot of the vessel	1.9 min.
Time for a QC to transfer an inbound container to a TR	1.9 min.
Turnaround time for a TR to the travel between the shore and the yard	10 min.
Time for a YC to receive an outbound container from an external truck	1.521 min.
Time for a YC to transfer an inbound container to an external truck	2.242 min.
Time for a YC to transfer an outbound container to a TR	1.134 min.
Time for a YC to receive an inbound container from a TR	1.114 min.
Storage duration of a container during a period (the length of a period)	24 hrs

***Tab. 6.** Percentage of inbound containers left the terminal on the n^{th} day after unloading*

n	1	2	3	4	5	6
Percentage (%)	34	22	15	14	11	4

***Tab. 7.** Resource profile for berthing a vessel (s_{Br}^{t}) (unit: minute)*

t	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
r													
H	–	–	–	–	–	–	324,00	–	–	–	–	–	–
C	–	–	–	–	–	–	1.9	–	–	–	–	–	–
R	–	–	–	–	–	–	10	–	–	–	–	–	–
Y	0.030	0.076	0.091	0.152	0.183	0.989	1.124	0.762	0.493	0.336	0.314	0.247	0.090
S	28.8	100.8	187.2	331.2	504	1,440	1,440	1,440	950.4	633.6	417.6	216	57.6

A numerical example is provided to illustrate a resource profile for a berth planning. We assume that the length of one period is 1 day, and the planning horizon is 14 days. Also, let us suppose that a vessel is scheduled to berth at the quay during period 7, 01:00~19:00. The total length of the quay is 1,500 m and thus the capacity of the berth is 1,500 × 1,440 m-min per period. The total number of slots in the SY is 21,000 slots. The SY consists of 20 storage blocks in which a storage block consists of 5 tiers, 6 rows, and 35 bays. Thus, the capacity of the SY becomes 21,000 × 1,440 slot-min per period. The number of QCs, TRs, and YCs is 15, 40 and 20 respectively. However, a QC has a schedule for preventive maintenances on periods 6, 7, and 8, and five TRs are expected to enter a maintenance shop for such preventive maintenances in periods 12, 13 and 14. The capacity of QCs, TRs, and YCs in a period can be evaluated by multiplying the total number of equipments with the length of a period, namely 21600, 57600 and 28800 machine-minutes, respectively. In the periods of 6, 7 and 8, the capacity of QCs becomes 20160 machine-minutes. In the periods of 12, 13 and 14, the capacity of TRs becomes 50400 machine-minutes.

Tab. 8 shows a part (periods 4 – 10) of an example in a capacity plan for the berthing of a vessel in the 7th day. The notations 'CP (capacity)', 'RS (reserved)', 'AV (available)', and 'RQ (requirement)' represent the total capacity of each resource during a period, the amount of the resource already reserved by other plans, the amount of available resource that is CP subtracted by RS, and the amount of the resource that will be reserved by the berthing of the vessel under consideration, respectively. Values in the 'RQ' are calculated by using the resource profile noted in Tab. 7 and the number of loading and unloading containers for the vessel noted in Tab. 5.

In Tab. 8, note that the resource requirements for the QCs and SY exceed their available capacities in the period of 7. Thus, we have to prepare extra QCs and storage spaces for containers in the period of 7 or reject the berthing of this vessel. Because a QC has a schedule for preventive maintenances in the period of 7, changes in a maintenance schedule for the QCs may solve these problems. Also, leasing the outside of SY (e.g. off-dock container yard) or reducing the dwell time of containers may increase in storage spaces for containers.

SCHEDULING OF QC WORKS (SPLIT)

Scheduling of QC works determines a schedule for each QC to discharge and load containers on a specific deck or in a specific hold of a vessel. We assume that a related berth plan has already been constructed. Tab. 9 shows the input parameters, decision variables, objectives, and constraints for scheduling of QC works.

For constructing a QC work schedule, a stowage plan for vessels and yard map in a SY must be provided. A stowage plan indicates the location of slots which containers must be discharged from or to be loaded in. A yard map shows storage locations of containers bound for a vessel. There may be some precedence relationships to be satisfied in unloading and loading tasks. For example, when a discharging operation is performed at a bay in a vessel, operations on a deck must be performed before the operations in hold of the same bay start. Also, loading operations in a hold must precede the loading operation on a deck of the same bay in a vessel. Because QCs travel on the same rail, two adjacent QCs must be apart from each other by at least a certain distance for them to simultaneously perform

Tab. 8. *Example of a capacity plan in a berth planning*

t	4	5	6	7	8	9	10
Berth							
CP	2,160,000	2,160,000	2,160,000	2,160,000	2,160,000	2,160,000	2,160,000
RS	1,857,600	1,978,560	1,918,080	1,797,120	–	–	–
AV	302,400	181,440	241,920	362,880	2,160,000	2,160,000	2,160,000
RQ	–	–	–	324,000	–	–	–
QC							
CP	21,600	21,600	20,160	20,160	20,160	21,600	21,600
RS	20,403	20,613	19,068	18,312	–	–	–
AV	1,197	987	1,092	1,848	21,600	21,600	21,600
RQ	–	–	–	**2,090**	–	–	–
TR							
CP	57,600	57,600	57,600	57,600	57,600	57,600	57,600
RS	46,890	47,340	47,115	43,185	36,540	36,240	36,075
AV	10,710	10,260	10,485	14,415	21,060	21,360	21,525
RQ	–	–	–	11,000	–	–	–
YC							
CP	28,800	28,800	28,800	28,800	28,800	28,800	28,800
RS	24,900	25,380	24,960	23,610	22,140	22,020	21,540
AV	3,900	3,420	3,840	5,190	6,660	6,780	7,260
RQ	82	99	534	1,236	427	276	188
SY							
CP	30,240,000	30,240,000	30,240,000	30,240,000	30,240,000	30,240,000	30,240,000
RS	28,800,000	29,160,000	29,088,000	28,800,000	28,080,000	27,720,000	27,360,000
AV	1,440,000	1,080,000	1,152,000	1,440,000	2,160,000	2,520,000	2,880,000
RQ	178,848	272,160	777,600	**1,584,000**	806,400	532,224	354,816

their operations without any interference. Planners attempt to construct in a way of minimizing the makespan in ship operations.

Tab. 9. Definition of the scheduling problem of QC works

Input parameters	Stowage plan of a vessel Available time window of each QC Yard map Resource profiles
Decision variables	Work schedule for QCs assigned to a vessel
Objectives	To minimize a make-span in ship operations
Constraints	Precedence relationships in operations Interference among QCs Availability of resources

Like in the berth planning, resource requirements depend on the number of unloading and loading containers and are evaluated by using a load profile for the scheduling of QC works. Requirements for each resource can be represented as shown in Figs 4-(a) and (b) that illustrate the resource profiles applied in inbound and outbound flows, respectively.

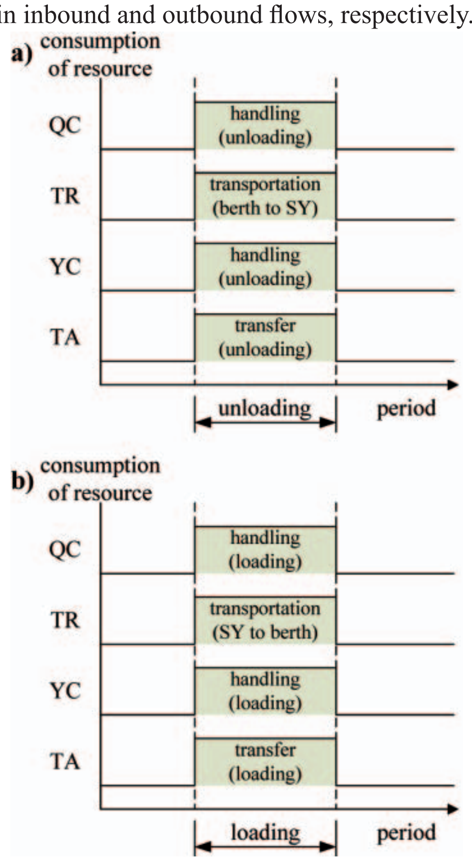

Fig. 4. Resource profile for unloading and loading operations in a vessel.
a) resource profile for inbound containers,
b) resource profile for outbound containers

During the process of the scheduling of QCs in advanced container terminals, blocks where inbound containers are unloaded and outbound containers are picked from each ship-bay are simultaneously determined. The availability of the resources in each corresponding block must be checked before the decision on the blocks is fixed. The resources in each block are YCs, TAs, and SY of each block. However, because the fleet of TRs may be operated in a pool for all QCs, the capacity of all TRs in a terminal are compared with the required amount of TRs during the ship operation.

Let $s^0_{QY_u}$ and $s^0_{QY_l}$ be the unit amount of the YC capacity required for transferring a container for unloading and loading operations that is required at the period when the ship operation occurs, respectively. $s^0_{QA_u}$ and $s^0_{QA_l}$ can be defined in the same way as previously mentioned ways. A resource profile can be evaluated as follows: s^0_{QC} can be evaluated by using {(the time for a QC to transfer an outbound container to a slot of a vessel) × (the percentage of loading containers among all containers for a QC) + (the time for a QC to transfer an inbound container to a TR) × (the percentage of unloading containers among all containers for a QC)}. Because TRs are required in loading and the unloading operations, s^0_{QR} can be evaluated in the similar way as s^0_{QC}. $s^0_{QY_u}$ and $s^0_{QY_l}$ can be evaluated by using the time for a YC to receive an inbound container from a TR and time for a YC to transfer an outbound container to a TR, respectively. Because TAs are consumed at the same period when YCs are required, $s^0_{QA_u}$ and $s^0_{QA_l}$ can be evaluated in the similar way as $s^0_{QY_u}$ and $s^0_{QY_l}$, respectively.

Tab. 10 summarizes data used for calculating the resource profile. For the transfer time of a QC, cycle time of a TR, and handling time of a YC, we used those in Tab. 5. Tab. 11 illustrates a resource profile in ship operations by QCs.

Tab. 10. Data used for calculating a resource profile in the scheduling of QC works

Number of loading containers for a QC	15 during period 3
Number of unloading containers for a QC	16 during period 3
Time for a TR to transfer a loading container in a TA	3 min
Time for a TR to transfer an unloading container in a TA	3 min

Tab. 11. Resource profile in ship operations by QCs (s^0_{Qr}) (unit: minute)

r	R	Y_u	Y_l	A_u	A_l
	10	1.114	1.134	3	3

We will introduce a numerical example to illustrate the resource profile applied to the scheduling of QC works. We assume that the length of one period is 1 hour, and a planning horizon is 12 hours. Also, let us suppose that a QC is scheduled to handle the containers during the period of 3. The capacity of a QC is 60 machine-minutes, the capacity of TRs is 2,400 machine-minutes, and the capacity of YCs in a storage block is 60 machine-minutes (refer to Section 3.1). Assuming that a storage block has 9 TAs and average occupation time of a TR in the TA is 3 minutes, the capacity of TAs in a storage block for a period can be obtained by multiplying the number of TAs in a storage block with the maximum number of TRs passing the TA for a period, namely, 180 machine-minutes.

The containers to be discharged or loaded by the QC will be located or are located in four different storage blocks as shown in Tab. 12. Tab. 13 shows an example of a capacity plan for the scheduling of QC works. Entries of 'RQ (requirement)' of each resource are calculated by using the resource profile in Tab. 11, number of loading and unloading containers for the QC in Tab. 10, and storage distribution of the containers for the QC in Tab. 12.

Tab. 12. Storage distribution of the containers for the QC

Storage block	1	2	3	4
Number of unloading containers	11	5	–	–
Number of loading containers	–	3	4	8

Tab. 13. Example of a capacity plan for the scheduling of QC works

a) TR

t	1	2	3	4	5	6	7	8	9	10	11	12
TR												
CP	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400
RS	1,967	1,963	1,800	1,523	1,517	1,511	1,509	1,503	1,503	1,501	1,500	1,359
AV	433	437	600	877	883	889	891	897	897	899	900	1,041
RQ	–	–	310	–	–	–	–	–	–	–	–	–

b) YC and TA in storage block 1

t	1	2	3	4	5	6	7	8	9	10	11	12
YC1												
CP	60	60	60	60	60	60	60	60	60	60	60	60
RS	53	52	50	46	46	46	46	45	45	45	45	44
AV	7	8	10	14	14	14	14	15	15	15	15	16
RQ	–	–	12	–	–	–	–	–	–	–	–	–
TA1												
CP	180	180	180	180	180	180	180	180	180	180	180	180
RS	107	103	128	133	133	133	132	130	129	129	129	126
AV	73	77	52	47	47	47	48	50	51	51	51	54
RQ	–	–	12	–	–	–	–	–	–	–	–	–

c) YC and TA in storage block 2

t	1	2	3	4	5	6	7	8	9	10	11	12
YC2												
CP	60	60	60	60	60	60	60	60	60	60	60	60
RS	53	51	50	46	46	46	46	45	45	45	45	44
AV	7	9	10	14	14	14	14	15	15	15	15	16
RQ	–	–	9	–	–	–	–	–	–	–	–	–
TA2												
CP	180	180	180	180	180	180	180	180	180	180	180	180
RS	108	103	88	125	125	125	125	123	122	122	121	120
AV	73	77	92	55	55	55	55	57	58	58	59	60
RQ	–	–	9	–	–	–	–	–	–	–	–	–

In Tab. 13 note that the resource requirements for the YCs in the storage block of 1 exceed the available capacity in the period of 3. Therefore, we have to deploy additional YCs in the period of 3. If other storage blocks can be used for unloading and loading containers in the period of 3, then the planner may modify the original schedule. Of course, the availability of the YCs and TAs must be checked again after the modification. Unfortunately, if a terminal cannot provide additional YCs in the period of 3, a certain part of work schedule in the period of period 3 must be moved to other periods.

YARD PLANNING

There are different types of yard plans depending on the handling facilities in a yard. However, most of yard plans specify, at least, the number of inbound containers to be discharged from each vessel and then stacked at each block, and the number of outbound containers bound for each vessel to be stacked at each block. Some yard plans may provide more detailed decisions on the storage, such as plans on storage layouts of outbound containers in each block. This paper assumes that a yard plan is constructed before containers bound for or discharged form a vessel start to arrive at a specific yard.

The decision on the exact storage location of an individual container is made in real time whenever a container arrives at a yard. Tab. 14 shows input parameters, decision variables, objectives, and constraints for a yard planning. For making a good yard plan, planners attempt to balance the workload in storage blocks and to minimize the travel distance for TRs to transport the containers between their storage blocks and berthing locations of the corresponding vessels.

Tab. 14. Definition of the problem in a yard planning

Input parameters	Number of outbound containers of each group that are bound for a vessel and will arrive at a terminal during each period Number of inbound containers discharged from a vessel during each period Resource profiles
Decision variables	Storage amounts for each group of containers to be stored in each storage block
Objectives	To balance workloads among storage blocks To minimize travel distances for TRs to transport containers between storage blocks and vessel berthing locations
Constraints	Availability of resources Storage capacity of each storage block Handling capacity of each storage block

The requirement of each resource can be determined as a time-phased way with respect to the arrival time of an

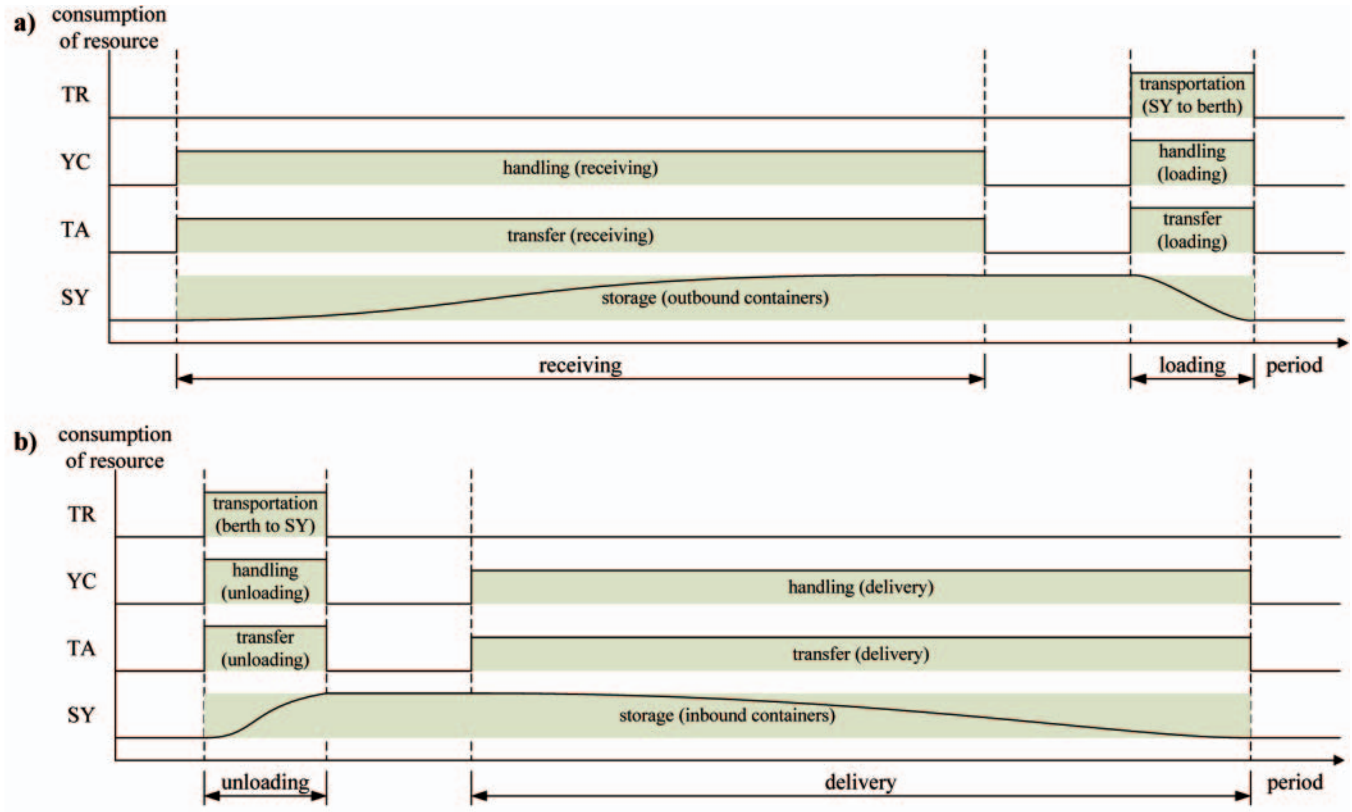

Fig. 5. *Resource profile for inbound and outbound containers.* ***a)*** *resource profile for outbound containers,* ***b)*** *resource profile for inbound containers*

outbound container or the discharging time of an inbound container. Figs 5-(a) and (b) illustrate a resource profile for outbound and inbound flows, respectively. As in the case of the scheduling of QC works, it is necessary to consider the YCs, TAs and storage spaces by each storage block and all TRs in a terminal. Decision variables in a yard planning are the number of outbound or inbound containers to be stacked at each block in each time period.

A resource profile for outbound containers can be evaluated as follows: s^t_{PR} for $t \geq 0$, can be evaluated by using the turnaround time for a TR to the travel between the shore and the yard. s^t_{PY} for $t \geq 0$ can be evaluated by (the transfer time for a YC to receive an outbound container) × (the percentage of containers, among all the outbound containers, arriving at the SY on the $(t + 1)^{th}$ period from the starting period of arrivals). s^t_{PY} for $t \geq 0$ can be evaluated by using the time for a YC to transfer an outbound container from a TR. Because TAs are required at the same period when YCs are required, s^t_{PA} for $t \geq 0$ can be evaluated in the similar way as s^t_{PY} for $t \geq 0$. s^t_{PS} for $t \geq 0$ can be evaluated by (the cumulative percentage of containers, among all the outbound containers, arriving at the SY until $(t + 1)^{th}$ period from the starting period of arrivals) × (the length of a period).

Second, a resource profile for inbound containers can be explained as follows: s^t_{PR} for $t = 0$ can be evaluated by using the time for a TR to the travel between shore and yard. s^t_{PY} for $t = 0$ can be evaluated by using the time for a YC to receive an inbound container from a TR. s^t_{PY} for $t > 0$ can be evaluated by using (the time for a YC to transfer an inbound container to an external truck) × (the percentage of containers, among all the inbound containers, leaving the terminal on the t^{th} period after unloading). Because TAs are consumed at the same period when YCs are required, s^t_{PA} for $t > 0$ can be evaluated in the similar way as s^t_{PY} for $t > 0$. s^t_{PS} for $t = 0$ can be evaluated by using the storage duration of the container for a period. s^t_{PS}, for $t > 0$, can be evaluated by {(1 – the cumulative percentage of containers, among all the inbound containers, having left the terminal until the $(t – 1)^{th}$ period after unloading) × (the length of a period)}.

Tab. 15 summarizes data used for calculating the resource profile. For the cycle time of a TR, handling time of a YC, and transfer time of a TR, we used ones in Tabs 6 and 11. Tabs 16 and 17 illustrate the resource profile for receiving and discharging of containers, respectively.

Tab. 15. *Data used for calculating a resource profile in a yard planning*

Number of receiving containers for a vessel	540
Number of unloading containers for a vessel	560
Time for an external truck to transfer a receiving container in a TA	3 minutes
Time for an external truck to transfer a delivery container in a TA	3 minutes
Storage duration of the container for a period	24 hours or 1,440 minutes

Tab. 16. *Resource profile for receiving an outbound container (s^t_{Pr}) (unit: minute)*

t	0	1	2	3	4	5	6
r							
R	–	–	–	–	–	–	10
Y	0.030	0.076	0.091	0.152	0.183	0.989	1.134
A	0.06	0.15	0.18	0.3	0.36	1.95	3
S	28.8	100.8	187.2	331.2	504	1,440	1,440

Tab. 17. Resource profile for discharging an inbound container (s^{i}_{Pr}) (unit: minute)

t	0	1	2	3	4	5	6
r							
R	10	–	–	–	–	–	–
Y	1.114	0.762	0.493	0.336	0.314	0.247	0.090
A	3	1.02	0.66	0.45	0.42	0.33	0.12
S	1,440	1,440	950.4	633.6	417.6	216	57.6

The following introduces a numerical example to illustrate a resource profile in a yard planning. We assume that the length of one period is 1 day and the planning horizon is 9 days. Let us suppose that a yard is scheduled to receive outbound containers from period 2 to 7 and to discharge inbound containers during the period of 2. The capacity of a storage block in the SY becomes 1,050 × 1,440 slot-minutes – a storage block with 5 tiers, 6 rows, and 35 bays. The capacity of TRs is 57,600 machine-minutes, the capacity of YCs in a storage block is 1,440 machine-minutes, and the capacity of TAs in a storage block is 4,320 machine-minutes.

Planners decide that inbound containers are stacked in 3 storage blocks, and outbound containers are stacked in 5 storage blocks as shown in Tab. 18. Tab. 19 illustrates an example of a capacity plan in a yard planning. Entries of 'RQ (requirement)' of each resource correspond to the amounts of the resources that are required for the storage in Tab. 18. The values in 'RQ' are calculated by using the resource profile in Tabs 16 and 17, the number of inbound and outbound containers that are planned to be stacked at the block 1 and 3 as shown in Tab. 18.

Tab. 18. Storage plans for inbound and outbound containers

Storage block	1	2	3	4	5	6	7
Number of inbound containers	220	200	140	–	–	–	–
Number of outbound containers	–	–	90	120	111	102	117

In Tab. 19 note that the resource requirements for the YCs and TAs in the storage block 1 exceed their available capacities in the period of 2. Therefore, we have to prepare extra YCs and TAs in other periods.

CONCLUSIONS

- For constructing an efficient operational plan in container terminals, a large number of factors must be considered for decision-making. Although various planning activities are mutually related with each other, they have been treated as independent decision-making processes. Furthermore, they often share the same resource that they have to compete with each other to secure.
- This study proposed a unified framework for integrating various planning activities in container terminals and defined decision-making problems in each planning

Tab. 19. Example of a capacity plan in a yard planning

a) TR

t	1	2	3	4	5	6	7	8	9
TR									
CP	57,600	57,600	57,600	57,600	57,600	57,600	57,600	57,600	57,600
RS	47,160	43,200	36,540	36,240	36,075	36,015	32,610	32,610	
AV	10,440	14,400	21,060	21,360	21,525	21,585	24,990	24,990	57,600
RQ	–	5,600	–	–	–	–	–	–	–

b) YC, TA, and SY in the storage block 1

t	1	2	3	4	5	6	7	8	9
YC1									
CP	1,440	1,440	1,440	1,440	1,440	1,440	1,440	1,440	1,440
RS	1,255	1,200	1,108	1,100	1,090	1,050	1,070	1,050	–
AV	185	240	332	340	350	390	370	390	1,440
RQ	–	**245**	168	108	74	69	54	20	–
TA1									
CP	4,320	4,320	4,320	4,320	4,320	4,320	4,320	4,320	4,320
RS	3,010	3,770	3,700	3,600	3,500	3,400	3,300	3,200	–
AV	1,310	550	620	720	820	920	1,020	1,120	4,320
RQ	–	**660**	224	145	99	92	73	26	–
SY1									
CP	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000
RS	1,157,000	1,140,000	1,104,000	1,103,000	1,102,000	1,101,000	1,100,000	1,099,000	–
AV	355,000	372,000	408,000	409,000	410,000	411,000	412,000	413,000	1,512,000
RQ	–	316,800	316,800	209,088	139,392	91,872	47,520	12,672	–

Tab. 19. Example of a capacity plan in a yard planning

c) YC, TA, and SY in the storage block 3

t	1	2	3	4	5	6	7	8	9
YC3									
CP	1,440	1,440	1,440	1,440	1,440	1,440	1,440	1,440	1,440
RS	635	640	520	510	500	490	480	470	–
AV	805	800	920	930	940	950	960	970	1,440
RQ	–	159	114	77	61	60	124	115	–
TA3									
CP	4,320	4,320	4,320	4,320	4,320	4,320	4,320	4,320	4,320
RS	3,450	1,900	4,000	3,900	3,800	3,700	3,600	3,500	–
AV	870	2,420	320	420	520	620	720	820	4,320
RQ	–	665	238	161	126	125	248	296	–
SY3									
CP	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000	1,512,000
RS	1,139,000	1,140,280	1,102,000	1,101,000	1,100,000	1,090,000	1,080,000	1,070,000	–
AV	373,000	371,720	410,000	411,000	412,000	422,000	432,000	442,000	1,512,000
RQ	–	2,592	9,072	16,848	29,808	45,360	129,600	129,600	–

activity. Input parameters, decision variables, objectives, constraints, time buckets, and planning horizon for each decision activity were identified. The concept of a resource profile was suggested that should be utilized to check the feasibility of a plan with respect to the constraint on the resource availability. Numerical examples were also provided to illustrate capacity planning procedures for a berth planning, scheduling of quay crane operations, and yard planning.

- The concept proposed in this study may be utilized for developing operational software for container terminals. Also, methods for optimizing various operational decisions by utilizing the concepts proposed in this study may be developed in future studies.

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