Satisfying Constraints for Locating Export Containers in Port Container Terminals

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Abstract. To allocate spaces to outbound containers, the constraint satisfaction technique was applied. Space allocation is pre-assigning spaces for arriving ships so that loading operations can be performed efficiently. The constraints, which are used to maximize the efficiency of yard trucks and transfer cranes, were collected from a real container terminal and formulated in the form of constraint. Numerical experiments were conducted to evaluate the performance of the developed algorithm.

1 Introduction

Operations in port container terminals consist of the discharging operation (during which containers are unloaded from ships), the loading operation (during which containers are loaded onto ships), the delivery operation (during which inbound containers are transferred from the marshalling yard to outside trucks), and the receiving operation (during which outbound containers are transferred from outside trucks to the marshalling yard). The discharging operation and the loading operation are together called the "ship operation." For sake of optimal customer service, the turnaround time of container-ships must be minimized by increasing the speed of the ship operation, and the turnaround time of outside trucks must be shortened as much as possible. Figure 1 shows a container yard.

In container terminals, the loading operation for outbound containers is carefully pre-planned by load planners. For the load planning, the responsible container-ship agent usually transfers a load profile (an outline of a load plan) to the terminal operating company several days before a ship's arrival. In the load profile, each slot (cell) is assigned a container group, which is identified by type (full or empty), port of destination, and the size of container to be stowed onto. Because a cell of a ship can be filled with any container within its assigned group, the handling work in the marshalling yard can be facilitated by optimally sequencing outbound containers for the loading operation. In sequencing the containers, load planners usually attempt to minimize the handling of quay cranes and the yard equipment. The output of this decision-making process is called the "load sequence list." To find an efficient load sequence, outbound containers must be laid out in the optimal location. The main focus of this paper is to suggest a method of pre-allocating storage space for arriving containers so that maximum efficiency is achieved in the loading operation.

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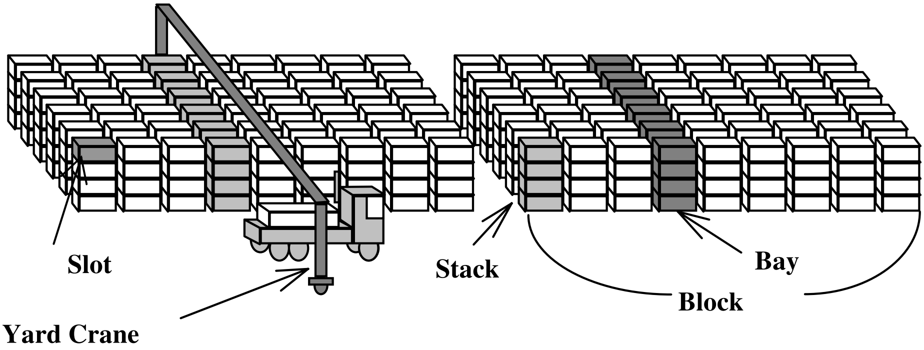

Fig. 1. An illustration of a container yard

In order to obtain an efficient load sequence, the following must be considered during the space planning process. Figure 2 shows a containership's cross-sectional view, which is called a ship-bay. The figure shows cells into which the containers of two groups (defined by size and port of destination) are assigned. A widely accepted principle for space planning is that yard-bays assigned to a containership should be located near the berthing position of the corresponding ship. In addition, there may be other principles of space planning that depend on the type of yard equipment. One such example is that containers of different groups should not be mixed in the same yard-bay. This principle is valid only for the indirect transfer (combined) system of yard-side equipment (yard crane or straddle carrier) and prime movers. During the loading operations of containers, containers of the same group are likely to be loaded onto cells located close together, as illustrated in Figure 2, and thus, the containers are usually loaded consecutively. Therefore, for the case of the indirect transfer system, the travel distance of the yard-side equipment can be reduced by placing containers of the same group in the same yard-bay. In addition, there are many practical rules that yard planners use for allocating spaces to different groups of containers. The rules will be discussed further in the following sections.

There have been many related studies regarding container terminals. Taleb-Ibrahimi [1] analyzed the space-allocation problem with a constant or cyclic space requirement for stacking containers. Kim and Kim [2] formulated a quadratic mixed-integer-programming model for the dynamic space-allocation problem, but they did not suggest an efficient algorithm for the mathematical model. Kim and Kim [3] addressed the space allocation problem for inbound container. Kim and Kim [4] discussed the factors that affect the efficiency of the loading operation of outbound containers. Kim et al. [5] suggested a method for determining storage locations for outbound containers so that the number of rehandles during the loading operation is minimized. Cao and Uebe [6] suggested a transportation model with a non-linear constraint for assigning available space to space requirements. However, they did not consider the dynamic aspect of container flows over the time horizon. Kozan [7] proposed a network model to describe the flow of containers in port container terminals. The model attempted to determine flows of different types of containers in a way that minimizes the total handling cost. Roll and Rosenblatt [8] suggested a grouped storage policy that is based on a concept similar to the space-allocation problem in container terminals. They applied the group storage strategy as a storage policy for warehouses. Tsang [9] described the constraint satisfaction technique in detail. Zhang *et al.* [10] discussed the storage space allocation problem in the storage yards of container terminals. They decomposed the space allocation problem into two levels: the subproblem in the first level attempts to balance workloads among different yard blocks, while the second subproblem minimizes the total transportation distance for moving containers between blocks and vessel berthing locations. Kim and Park [11] proposed a multicommodity minimal cost flow problem model for the space allocation problem. A subgradient optimization technique was applied to solve the problem.

All the previous studies assumed that the objective function is clearly defined, and that feasible solutions can be easily obtained. However, in container terminals, there are many complicated constraints to be satisfied, and so, finding a feasible solution itself is a difficult problem. This is why CSP technique is applied to the space allocation problem in container terminals.

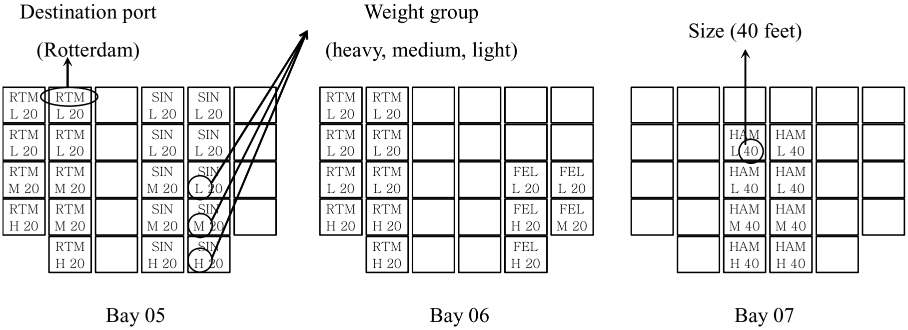

Fig. 2. An example of a stowage plan of a container-ship

2 Space Allocation Problem for Export Containers

It is assumed that the allocation of space is performed periodically. The length of the allocation period may be one day, 12 hours, or 6 hours, depending on the level of uncertainty and the time of the computation. Each period is called a "stage" in the decision-making process of space allocation.

The level of inventory in containers that arrive at a container yard follows a similar pattern. Arriving containers are classified into container groups, each of which is a collection of containers of the same length, vessel, and destination port. It is also assumed that containers of different groups are not stacked in the same yard-bay. The space must be pre-allocated for each group of containers that will arrive during the next stage. However, if decisions for the next stage are made without considering future changes in the yard, it may be impossible to find a feasible solution for the succeeding stages. Thus, an investigation must be performed on the effects of the decisions for the next stage on those for the subsequent stages. In this study, the investigation is performed by the CSP technique.

By using the forecasted arrival of containers, space requirements are estimated for each group of containers that will arrive at the yard in the next stage and the subsequent stages. A container group that requires an allocation of space is called an SDU (Space Demand Unit). The amount of space needed by each SDU is expressed in the unit of one yard-bay for 20-ft containers and two yard-bays for 40-ft containers. Based on the expected arrival of containers, SDUs for the next stage and the subsequent stages, all of which represent the demand side of the space allocation, must be specified.

Next, the supply side of space allocation must be considered. A container yard for outbound containers is usually divided into several blocks, each of which consists of 20 to 30 yard-bays. Each yard-bay consists of 20 to 30 stacks in a straddle carrier system and 6 to 8 stacks in a yard crane system. Space can be allocated in units of stacks or yard-bays, depending on the type of handling equipment and the space-allocation strategy used. In this study, a yard-bay is considered to be the unit of space allocation (SAU). Figure 3 shows the conceptual representation of the space allocation for this study. The space allocation assigns one or two available SAUs to an SDU. No SAU can be assigned to more than one SDU.

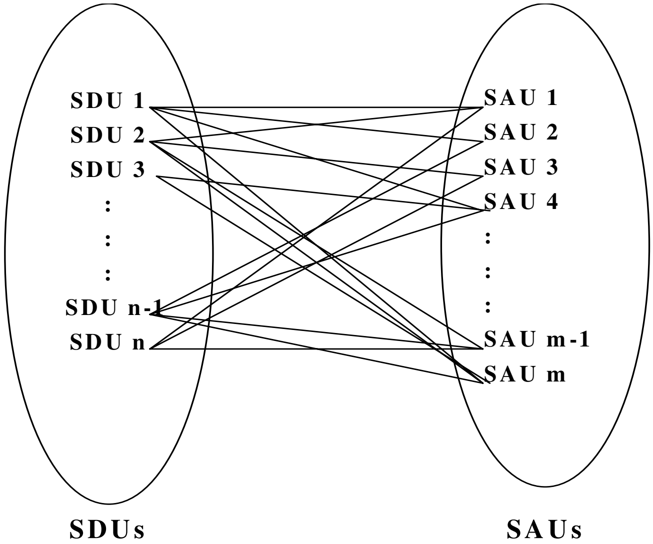

Fig. 3. Matching SDUs with SAUs

One of the difficulties of the space allocation problem is that the quality of the allocation decisions can be evaluated only when the loading operation is performed. However, the efficiency of the loading operation is dependent on the load sequencing of the outbound containers as well as the allocations. Because load sequencing is another complicated decision-making problem and there are many complicated constraints to be satisfied for the space allocation, the optimization is not a practical approach for the space allocation problem.

This paper discusses how the technique for the constraint satisfaction problem (CSP) can be applied to the space allocation problem. The following explains the constraints that were collected from an actual container terminal. Most of the constraints are related to rules that have been used for a long time by yard planners for efficient loading operations in container terminals.

(Constraint 1) The distance between the berth that a vessel arrives at and the location of a block where the outbound containers of the vessel are stacked must be less than a specified maximum limit. This constraint is necessary to reduce the travel cost of yard trucks between the apron and the yard.
(Constraint 2) The maximum distance between blocks where containers for one vessel are located must be less than a specified value. This constraint is necessary to reduce the travel distance of transfer cranes.
(Constraint 3) Containers for one vessel must be stacked in the blocks that are located in the same row of the yard. This constraint is necessary because transfer cranes can travel more easily in the lengthwise direction of blocks than in the widthwise direction of blocks.
(Constraint 4) A block's space cannot be allocated to the receiving operation of a vessel when the loading operation of another vessel is scheduled at the same time at the same block. This constraint is necessary to prevent the congestion of transfer cranes in the same block.
(Constraint 5) The number of vessels onto which containers stacked in a block will be loaded cannot exceed a specified limit (NV_{max}). This constraint has the effect of simultaneously restricting both the maximum number of blocks to be allocated to a vessel and the minimum number of containers to be stacked for a vessel.
(Constraint 6) The number of blocks, in which the containers to be loaded onto the same vessel are stacked, cannot exceed a specified limit (NB_{max}). When the containers for one vessel are scattered over too many blocks, the travel distance of the transfer cranes may be excessive.
(Constraint 7) A 40-ft container requires two consecutive 20-ft yard-bays.

In addition to the above constraints, other constraints can be additionally considered without significantly modifying the search algorithm.

3 Application of the CSP Techniques to the Allocation of Spaces

Figure 4 shows the structure of the program developed for the space allocation problem. The system consists of an interface layer, a constraint specification layer, and a search layer. In the interface layer, variables and their domains are specified. In the space allocation problem, variables correspond to SDUs, while the domain of an SDU corresponds to SAUs that can be allocated to the SDU. In the constraint specification layer, constraints, which are expressed in the form of equations, are specified. Various program modules are already provided and can be easily used only by specifying the values of parameters.

The following describes the search procedure in this study:

Step 1: Define the variables and domain, which is a set of values that the variable can take, of each variable.

Step 2: If there remains no more variable, then stop. Otherwise, select the next variable.

Step 3: Select the next value. Assign the selected value to the variable. If all the variables are assigned values, then stop. Otherwise, go to Step 4.

Step 4: Reduce the problem. In this step, values of the remaining variables, which do not satisfy at least one constraint, will be removed from the domains of the variables. Check if there is a variable whose domain becomes empty. If yes, then go to Step 5. If no, then go to Step 2.

Step 5: Check if there remains any value to assign for the current variable. If yes, then go to Step 3. If no, then let the current variable be the previous variable (backtracking) and go to Step 3.

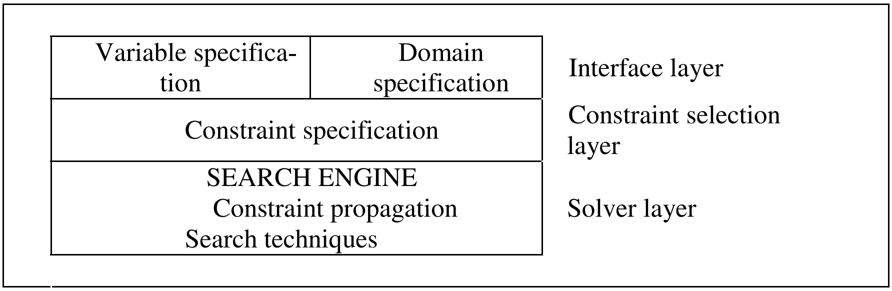

Fig. 4. The structure of the program developed for the space allocation

4 Numerical Experiment

Numerical experiment was conducted to test the performance of the search algorithm and find the best search strategies.

4.1 Input Data for the Numerical Experiment

The algorithm developed in this study was applied to solve a real space allocation problem of a large container terminal (PECT: Pusan Eastern Container Terminal) in Pusan. Various search strategies were tested to evaluate the speed of the search algorithm. The strategies used were variable-ordering rules, value-ordering rules, and constraint-ordering rules. A problem with two stages, 84 variables (SDUs) which approximately equal to 15 (vessels) × 2 (sizes) x 3 (destination ports), and 600 values (SAUs) of each variable, which corresponds to the number of bays in the yard, was solved. The data set came from a practical case with 15 vessels and 24 blocks, and 4 berths. The problems in the experiment considered all seven constraints mentioned in section 2. Parameters for constraints 5 and 6 were set as follows: $NV_{max} = 3$ and $NB_{max} = 3$.

4.2 Experiment to Evaluate Various Variable-Ordering Strategies

The following three criteria were used for ordering variables.

(1) Stage of SDU: The SDUs of earlier stages have higher priorities than those of later stages.
(2) Size of containers of SDU: The SDUs of 40-ft containers have higher priorities than those of 20-ft containers.
(3) Vessel of SDU: The SDUs of vessels arriving at a terminal are prioritized based on chronological order.

By combining the three different criteria, three variable-ordering rules were constructed as follows:

(Rule 1) Sequence SDUs according to the stage criteria.
(Rule 2) Sequence SDUs according to the size criteria.
(Rule 3) Sequence SDUs according to the stage criteria first, and followed by the vessel criteria.
(Rule 4) Sequence SDUs according to the stage criteria first, the vessel criteria second, and the size criteria third.

SDUs with the same values of sequencing criteria are sequenced in a random order. The values in the domains are sequenced in the order of increasing bay ID. The problem was solved for ten initial distributions of containers. Results in Table 1 show the CPU time to find a feasible solution for ten problems.

Through a statistical test, three null hypotheses that the computational time by rule 4 is not greater than that by each of the other three rules were rejected under the significance level of 1%. The results of the hypothetical test imply that using rule 4 results in a shorter computation time, compared to the other rules.

Table 1. The computational time for various variable-ordering rules (in seconds)

Initial distribution	Rule 1	Rule 2	Rule 3	Rule 4
1	654	596	556	497
2	670	602	570	521
3	643	579	554	504
4	665	588	586	487
5	663	607	564	479
6	657	577	565	518
7	655	589	573	510
8	647	590	546	496
9	660	610	577	488
10	662	588	573	505
Average	658	593	566	501

4.3 Experiment to Evaluate Two Value-Ordering Strategies

An experiment was performed on different sequences of values in the domains. Rule 3 was used as the variable-ordering rule. Two rules for value-ordering were compared with each other. The first rule is to sequence SAUs in the alphabetical order of the bay ID, and this rule will be called the "bay ID rule." The second rule is to give higher priorities to SAUs that are located in the blocks nearer to the berthing location of the vessel corresponding to the SDU. The second rule will be called the "closest-to-berth rule."

As in the case of the first experiment, ten problems with different initial distributions of stacked containers were solved. The results of the numerical experiment are shown in Table 2.

Table 2. The computational time for two value-ordering rules (in seconds)

Initial distribution of containers	Bay ID rule	Closest-to-berth rule
1	556	537
2	570	546
3	554	532
4	586	566
5	564	563
6	565	535
7	573	549
8	546	532
9	577	545
10	573	558
Average	566	543

By a statistical test, it was concluded that the closest-to-berth rule outperforms the bay ID rule in computational time under the significance level of 1%.

4.4 Experiment to Evaluate Various Constraint-Ordering Strategies

There are many constraints that solutions of the space allocation problem must satisfy. The propagation sequence of constraints during the search process is expected significantly affect the computational time, which will be tested in this subsection. Constraints 3, 5, 6, and 7 were considered. It was assumed that $NV_{max} = 3$ and $NB_{max} = 3$. Rule 3 and the bay ID rule were used as the variable-ordering rule and the value-ordering rule, respectively.

For each sequence of constraints, ten problems with different initial distributions of containers were solved. Table 3 shows the average computational time of the ten test problems for different sequence of constraints. The table shows that the sequence of constraints significantly affects the computational time and that constraint 5 should be propagated first during the search process.

Table 3. The computational time for different sequences of constraints

Seq.	Sequence of constraints	Search time (in *s*)	Seq.	Sequence of constraints	Search time (in *s*)
1	5→7→6→3	465	13	3→6→7→5	564
2	5→6→3→7	472	14	3→5→6→7	567
3	5→7→3→6	477	15	3→7→5→6	567
4	5→3→7→6	497	16	3→7→6→5	570
5	6→5→3→7	498	17	3→5→7→6	584
6	5→3→6→7	501	18	3→6→5→7	592
7	5→6→7→3	503	19	7→5→3→6	598
8	6→7→5→3	509	20	7→3→6→5	607
9	6→7→3→5	512	21	7→3→5→6	612
10	6→3→5→7	513	22	7→5→6→3	629
11	6→3→7→5	520	23	7→6→5→3	630
12	6→5→7→3	532	24	7→6→3→5	632

5 Conclusions

The constraint satisfaction problem (CSP) technique was applied to a space allocation problem for outbound containers. A program that realized the CSP concept was developed for the space allocation. Constraints for the space allocation problem were introduced.

Using real data collected from the Pusan Eastern Container Terminal, Korea, numerical experiments were conducted to evaluate the performance of the developed algorithm. Various variable-ordering rules were compared with each other in terms of their computational time. The results showed that sequencing space demand (requirement) units by the stage criteria first, the vessel criteria second, and the size criteria third results in the shortest computational time. It was also shown that the value-ordering rule significantly affects the computational time. Lastly, various sequences of constraint propagation during the search process were compared with each other. It was also shown that the sequence of constraints significantly affects the computational time.

Acknowledgments

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