ARRANGING MASTER BAY PLANS FOR LARGE CONTAINER SHIPS USING A MULTI-COMMODITY NETWORK

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Abstract: This study proposes a mathematical model to arrange the master bay plans for large container ships. With the advantages of an underlying multi-commodity network structure, solutions can be obtained within reasonable computation times when making master bay plans for ships with a capacity of 14,000 twenty-foot equivalent units, which is currently the predominant type of ocean-going ships. In addition, 40-foot and 40-foot high cubic containers, which are critical container types in use but have rarely been discussed in the existing literature, were addressed efficiently in the proposed model by adding specially designed arcs and side constraints.

Keywords: Containers, Liner Shipping, Stowage Planning, Multi-Commodity Network

I. INTRODUCTION

Liner shipping has become the most important mode for transporting cargos globally because containers can be conveniently exchanged among trucks, ships and trains. In the early times of contained use, they were loaded and tied up simply on general cargo ships because the number of containers was quite low. However, as the demand for container shipping increased dramatically over the last six decades, such a simple stowage method could not offer sufficient capacity and safety. Therefore, after a short transition period of using semi-container and convertible ships, the so-called fully cellular container ships have become the predominant ship type in the liner shipping industry. With specially designed guide rails fixed vertically in the cargo holds, containers can be easily put into a hold and fixed safely without using twist-locks between containers in the same stack. In addition, the standard devices such as twist-locks and various fittings and lashing gears enable containers to be stacked high above a ship's deck; as a result, a full container ship can carry a large number of containers by stacking them tightly and vertically both on the deck and in the holds. Although the capacity of full container ships has increased significantly, the container loading and discharging (LD) cannot be performed efficiently if the stowage slots of each container are not arranged carefully and appropriately in advance. That is, so-called over-stowages occur in which some containers block the target container that is going to be lifted out. Therefore, minimizing over-stowages has become an important concern of liner carriers and terminal operators to increase the efficiency of container LD and save costs. The best way to minimize over-stowages is to design good stowage plans before the actual LD begin. Initially, when ships were small and had few ports of call, their stowage plans were made directly including the stowage positions, stability and even LD sequences. However, because modern container ships are now larger, such thorough planning methods cannot meet the efficiency requirements of liner carriers and terminal operations. The reason is that the direct stowage planning problem is an NP-complete problem (Wilson and Roach, 1999; Avriel et al., 2000), that is, a problem for which it is difficult to obtain the optimal solution within a reasonable time when facing large problems. As a result, a two-phase planning is now used widely which comprises *master planning* and *detailed planning*. This study aims at addressing the first-phase planning, the master plan. With an underlying network structure, our proposed model can take into account many important determinants, especially the container size, which has seldom been discussed in the literature.

II. LITERATURE REVIEW

The earliest research on stowage planning was by Webster and Van (1970), who focused on shipside LD. They divided the system into two components: the ship and the container. The first component focused on maintaining a ship's stability, which is important for navigation, and the other component discussed the placement of containers with three aims: to minimize over-stowages of containers between their OD ports;

to minimize the total handling time by combining LD operations; and to maximize the utilization of ship space within the container placement restrictions. In terms of over-stowages, Webster and Van (1970)suggested keeping similar containers heading to the same destination within slots for the entire group. Based on the third aim, Aslidis (1989) further explained that when mixing is required, containers for more distant ports should be loaded beneath those for nearer ports.Wilson and Roach (1999, 2000) and Wilson et al. (2001) applied combinatorial optimization to address container stowage planning problems. They devised a two-stage Tabu search heuristic to find good solutions in reasonable times. Rather than assigning individual containers to each slot exactly, the first stage categorized all containers into groups and then assigned these container groups to the slots also categorized into groups called blocks. This procedure reflects the practice of human planners, which can effectively reduce solution times. Then, the exact slots for individual containers were determined in the second stage. We adopted these authors' idea of two-phase planning in this study because it is more suitable for resolving stowage planning problems on large ships. Although the previously discussed proposed model did consider container size and the movements of hatch covers, its applicability was limited because of its low solution efficiency: a small test sample based on a 688 TEU ship still took 30 minutes to obtain the optimal solution. Meanwhile, the model attempted to maximize the number of QCs in operation at each port of loading, which can distribute the containers from a specific loading port to too many bays, which tends to increase hatch cover movements.Considering hatch covers, container weights and types,Ambrosino et al. (2013)established two mixed integer programming models to arrange the master bay plan directly without separatingthe process into two phases. They proposed two heuristics to solve the problem because the solution cannot be found within a reasonable time.The maximal test case was based on a 5,280 TEU ship. It's worth noting that, though container type was taken into account by the proposed models, theydealt with only 20' and 40' containers., the 40' high cubic (hereafter called 40' HQ)container, which is also commonly used in practice, was not considered in their models.

III. METHODOLOGY

Firstly, we define the following decision variables, sets and parameters:

(1) Decision Variables

x_{ij}^{od} : The number of containers flowing from node *i* to node *j*on the layer that indicates the sailing leg from port *o* to port *d*.

y_{ij}^{od} : A binary variable indicating whether or not the block control arc that connects node *i* to node*j* on the layer that indicates the sailing leg from port *o* to port *d* is used. Containers are allowed to flow through a block control arc if and only if its corresponding y_{ij}^{od} equals 1.

z_{ij}^{od} : A binary variable indicating whether or not the bay collection arc that connects node *i* to node *j* on the layer that indicates the sailing leg from port *o* to port *d* is used. Containers are allowed to flow through a bay collection arc if and only if its corresponding z_{ij}^{od} equals 1.

(2) Parameters

c_{ij}^{od} : The unit cost for containers flowing from node *i* to node*j*on the layer that indicates the sailing leg from port *o* to port *d*.

d_{ij}^{od} : The number of containers expected to be carried from node *i* to node*j*on the layer that indicates the sailing leg from port *o* to port *d*.

u_{ij} : The upper bound of the block assignment arc (*i*, *j*).

q : Total number of containers

M : A big number

(3) Notations

o: a loading port
d: a discharging port

(4) Sets

A : The set of all arcs

A_B : The set of all bay collection arcs

A_b : The set of all block assignment arcs that connect to above-deck blocks

A_b^4 : The set of block assignment arcs that indicate 40' containers

A_b^H : The set of block assignment arcs that indicate 40' HQ containers

A_b^C : The set of all block control arcs

A_D : The set of all OD arcs

OD : The set of all OD port pairs

B : The set of all bays

N : The set of all nodes

D : The set of all discharging ports

O : The set of all loading ports

S: The sink node

T: The collection node

Based on the above definitions and the proposed multi-commodity network, a master bay planning problem can be formulated as follows:

$$Min \sum_{(o,d)\in OD} \sum_{(i,j)\in A_b} c_{ij}^{od} x_{ij}^{od} + \sum_{(o,d)\in OD} \sum_{(i,j)\in A_B} z_{ij}^{od} \quad (1)$$

s.t.

$$\sum_{(i,j)\in A} x_{ij}^{od} - \sum_{(i,j)\in A} x_{ji}^{od} = \begin{cases} q, & if\, i = S \\ -q, & if\, i = T \\ 0, & otherwise \end{cases} \quad (2)$$

$$x_{ij}^{od} = d_{ij}^{od} \quad \forall (i,j) \in A_D, \forall (o,d) \in OD \quad (3)$$

$$x_{ij}^{od} = x_{pd}^{od} \quad \forall (i,j) \in A_b^4 \cup A_b^H, \ \forall (o,d) \in OD, \ (p,d) = paired(i,j) \quad (4)$$

$$\sum_{(o,d)\in OD} x_{ij}^{od} \le u_{ij} \quad \forall (i,j) \in A_b \quad (5)$$

{ $(x_ij\^od \le M \cdot y_ij\^od \quad \forall (i,j) \in A_b\^U, \forall (o,d) \in OD @ \sum_(k = d+1)\^D x_pq\^ok \le M \cdot (1 - y_ij\^od)\ (p,q) = paired(i,j), \forall (o,d) \in OD)$ ┤ (6)

$$x_{ij}^{od} \le M \cdot z_{ij}^{od} \quad \forall (i,j) \in A_B, \forall (o,d) \in OD \quad (7)$$

$$x_{ij}^{od} \ge 0 \quad \forall (i,j) \in A, \forall (o,d) \in OD \quad (8)$$

$$y_{ij}^{od} \in \{0,1\} \quad \forall (i,j) \in A_b^C, \forall (o,d) \in OD \quad (9)$$

$$z_{ij}^{od} \in \{0,1\} \quad \forall (i,j) \in A_B, \forall (o,d) \in OD \quad (10)$$

Eq (1) is the objective function that minimizes the total cost, which is composed of the assignment cost and the cost of using extra bays. Eq (2) is the flow conservation constraint because the proposed model has an underlying network structure. Eq (3) guarantees that the containers can flow through their specific OD port pairs. Eq (4) ensures that each paired front and rear block must be occupied simultaneously while storing 40' or 40' HQ containers because they need two TEUs of space for a pair of these blocks. Eq (5) limits the number of containers stored in any block to its capacity. Eq (6) prohibits over-stowages while discharging containers by using binary variables to control the paired block control arcs. That is, once an under-deck block has been occupied by containers heading to a port, then any containers heading to more distant ports cannot be put on the paired above-deck block because its corresponding binary variables will become zero. Eq (7) reflects the usage of bays; a bay is available if and only if its corresponding binary variable equals one. The last three constraints focus on the decision variables. Eq (8) requires that the container flows on all arcs be nonnegative rather than integers; however, taking advantage of the integer solution property of minimum-cost flow problems, all arc flows will still be integers without applying integer programming, which needs much longer solution time. Eqs (9) and (10) limit the control variables that correspond to the block control and bay collection arcs to being binary.

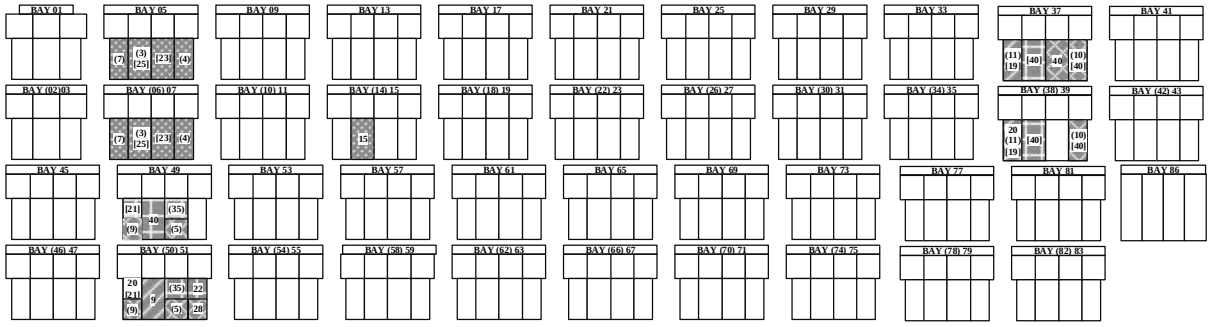
IV. EMPIRICAL STUDY

We empirically tested the real case of the Asia–Europe express service (AES) operated by liner A to examine the performance of our proposed model. The AES connects five ports in Asia to four ports in Europe. Among the five loading ports in Asia, containers are mainly loaded from KHH, HKG and YTN. In total, 11,393 TEUs of 20', 40' and 40' HQ containers are planned to be loaded from Asia. In terms of the destination ports, most containers are heading to RTM and HAM. The ship deployed by AES is composed of 44 bays in terms of TEU. Because one 40' or 40' HQ container must occupy two paired adjacent bays, the number of bays reduces to 22 in terms of forty-foot equivalent units, in which the last bay in the stern is reserved for 40' containers exclusively owing to the ship's structure. Each bay is composed of eight blocks except bays 01, 02 (03) and 86 owing to the ship's structure, and the bays amidships provide larger capacity than those close to the bow and stern.According to the proposed model, the master bay planning problem in the basic scenario was transformed to a minimum-cost flow problem with 110,391 decision variables and 27,041 constraints; we used Gurobi 6.0 package to solve the problem and found the optimal solution within 601.17 seconds with a personal computer equipped with Intel Core i7-4790 CPU and 32 gigabytes of memory. The

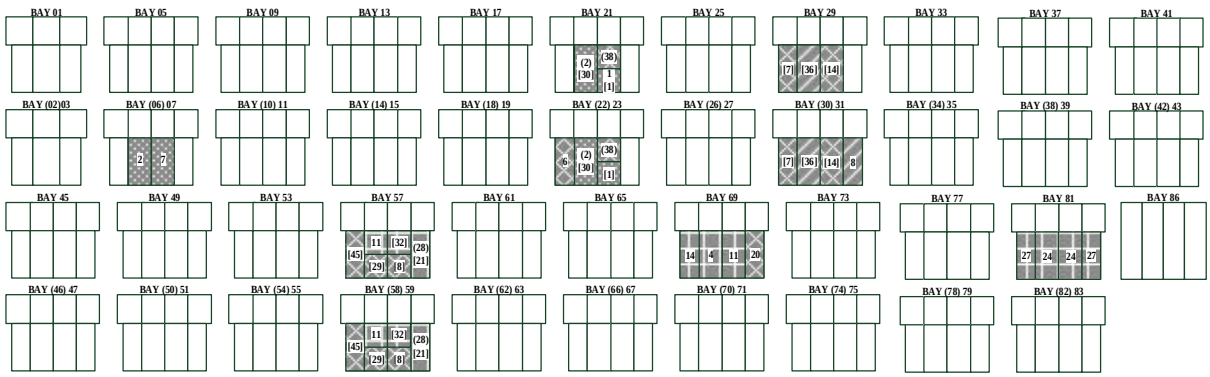
best objective value was 40,725, with a gap of 0.243%. Figure1 illustrates the optimal solution of the basic scenario by the calling sequence of all loading ports; the discharging ports are distinguished by shaded patterns. The quantity of containers that should be loaded to each block is marked with three types of numbers, in which those without parentheses indicate the quantity of 20' containers and the quantities of 40' and 40' HQ containers are marked with parentheses and square brackets, respectively.

CONCLUSIONS

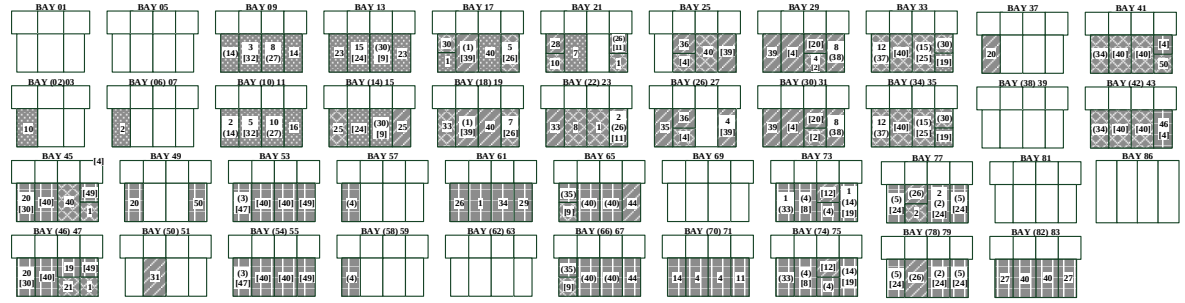
In this study, we formulated the first planning phase as a minimum-cost flow problem based on a multi-commodity network, which contributes to the literature in two ways. First, the underlying network structure of the proposed model can effectively shorten the solution time; in our empirical test, it took 601.17 seconds to find the optimal solution based on a ship with a capacity of 14,000 TEU, which is acceptable in practice and faster than test cases 11, 19 and 20 in Pacino et.al (2011), which were based on ships with capacities of around 9,000 TEUs; however, their cases were not identical to ours. Second, due to the changeable patterns of master bays, it is complex to take into account 40' and 40' HQ containers when modelling stowage planning problems. The value and applicability of a model are limited if it cannot efficiently address 40' and 40' HQ containers because most shipments are composed of 20', 40' and 40' HQ containers. To our knowledge, only a few studies have discussed how to consider 40' containers in stowage planning (Ambrosino et al., 2004 and 2006; Sciomachen and Tanfani, 2007), and these were based on ships with a capacity of 198 TEUs. In addition, 40' HQ containers have not been discussed in the literature related to stowage planning. In the present study, based on a network structure and side constraints, our proposed model could efficiently arrange the storage locations for 40' and 40' HQ containers while making master plans for a large ship with a capacity of 14,000 TEUs, which contributes to the literature. Although the proposed model has sound performance, there is still room for improvement in future studies. First, based on the multi-commodity network structure we proposed in this study, more container types (e.g. reefer containers) can be included in the model, although the solution time is expected to increase because more side constraints will limit decision variables across layers. Accordingly, future studies may develop heuristics to find solutions within reasonable times. Second, the model we developed in this study is for one voyage only. Because some liner services are designed as loops, a new voyage will begin immediately when a ship departs from the last port of the previous voyage, and therefore, the model's planning horizon could extend to cover two or more voyages to reflect the real scenario. In addition, developing solution strategies on a rolling horizon basis is also a highly relevant issue for future studies.



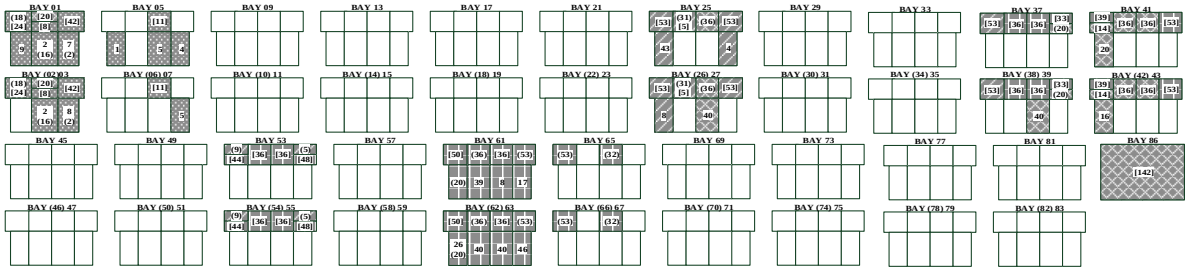
(a) Optimal stowage pattern (Hong Kong)



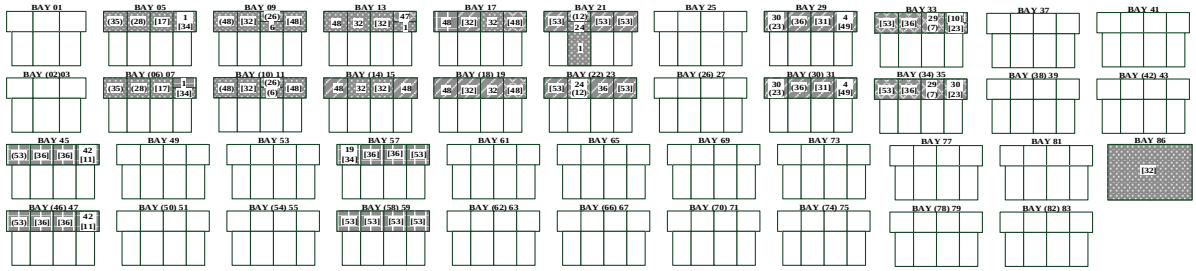
(b) Optimal stowage pattern (Nansha)



(c) Optimal stowage pattern (Kaohsiung)



(d) Optimal stowage pattern (Yantian)



(e) Optimal stowage pattern (Singapore)

Remarks: Piraeus Rotterdam Hamburg Antwerp

1. Numbers without parentheses refer to the number of 20-foot containers.
2. Numbers in parentheses refer to the number of 40-foot containers.
3. Numbers in square brcketsrefer to the number of 40-foot HQ containers.

Figure 1The optimal solution of the basic scenario

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