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Stowage Planning to Minimize Travelling Energy Consumption of Terminal Vehicles

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Abstract

The increasing size and complexity of modern container ships necessitate more efficient and sustainable terminal operations. This study addresses the detailed stowage planning problem from the perspective of terminal planners, with a novel objective: minimizing the energy consumption of container handling vehicles operating between yard positions and quay-side loading bays. A Mixed Integer Linear Programming (MILP) model is proposed to optimize container-to-slot assignments, considering compatibility constraints, weight distribution, and predefined aggregate stowage plans. The objective function combines a lexicographic penalty scheme prioritizing plan adherence with a distance-based energy cost minimization. The model explicitly integrates operational constraints related to stack formation and stability while ensuring feasibility through soft constraints for deviations and unassigned containers. Computational experiments on a realistic dataset comprising 329 containers demonstrate the model's effectiveness, achieving an optimal solution in under a few minutes with no unassigned containers and minimal deviation from the aggregated plan. Results confirm that the proposed approach enables energy-efficient container allocation without compromising operational constraints, offering a promising direction for green port operations.

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Keywords: Stowage planning; Energy efficiency; Mixed integer linear programming model

1. Introduction and Literature review

Since the beginning of this century, the demand for maritime transport has been rising continuously, so much that the world's fleet of container ships has grown in terms of total capacity, entering the so-called mega-ship era, resulting in container ships with a capacity of 20,000 TEUs. Such large ships require an efficient handling service, which calls for the synchronisation and optimisation of all operational activities carried out in the berthing area (Steenken et al., 2004; Imai et al., 2013). In this context, stowage planning is a key factor to determine the operational cost of both

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container ships and terminal operators (Monaco et al., 2014). The stowage planning problem, first introduced in (Avriel et al., 2000), consists of defining the placement of containers within a container ship during its journey. It is a very complex task requiring detailed information concerning the container ship, the terminals involved in its journey, and all containers travelling on board, such as their type, size, weight, and destination. The NP-hardness of this problem has been proved in (Tierney et al., 2014). In the literature, many heuristic approaches have been proposed to deal with stowage plannings involving large-size instances. Among others, we mention (Ambrosino et al., 2010) and (Ding and Chou, 2015), in case of single port planning, and more recently (Ambrosino et al., 2017), and (Parreño-Torres et al., 2021) for multi-port stowage planning. For a recent and complete survey on the stowage planning problem, readers can refer to (van Twiller et al., 2024). Stowage planning involves two different decision makers, that is, the shipping line coordinator (SC) and the terminal planner (TP). The SC repeatedly refines the vessel's stowage plan to accommodate new origin-destination bookings, while respecting capacity, stability, and terminal-efficiency constraints. A few hours before berthing, the SC issues a stowage plan that groups containers by destination, type, size, and weight and assigns each group to a general ship section. SC has a complete view of all containers to be loaded /unloaded at each port the container ship calls during its journey, and the structure of the container ship. Moreover, SC receives the origin–destination transport demands. In this phase, SC also has to verify whether it is possible to accept each transport demand, and in case of dangerous goods, the SC must follow precise rules for storing them on board, according to the segregation table of the International Maritime Dangerous Goods Code (Ambrosino and Sciomachen, 2021). The TP then converts these guidelines into exact bay-row-tier positions for every container. The activity of the TP starts after having received the stowage instructions from the SC. Indeed, TP is responsible for determining the detailed stowage plan for a container ship at the current port of the journey within a circular route, defining in which locations the containers loaded in that port must be positioned. It is worth noting that stowage planning is a major issue not only for shipping companies, but also for terminal operators, who are involved in loading, unloading, transporting, and storing thousands of containers. To remain competitive, terminal operators aim to offer a high level of service to container ships and make efficient use of terminal resources such as berths, quay cranes, space, and yard equipment. Until a few years ago, stowage planning had the sole aim of reducing the stay of container ships in port (Delgado et al., 2012; Meisel, 2009). For this reason, many works focused on the integration between stowage planning, handling operations, and vehicle scheduling in order to speed up the loading / unloading operations at a port (see, e.g. (Azevedo et al., 2018; Iris et al., 2018; Jin et al., 2024)). Nowadays, however, in addition to port efficiency, it is also crucial to pay attention to environmental sustainability when determining the stowage plan. In particular, more and more attention is now being paid to improving environmental sustainability in the handling of container ships, as has previously been the case in the manufacturing sector for the planning of production operations (Paolucci et al., 2017). In the case of maritime logistics, the aim is, therefore, to minimize the energy consumption of all means of transport involved directly or indirectly in the loading of a ship. In particular, considering the reduction of CO_2 emissions of major terminal equipment as an objective has been shown to be relevant for the advancement of green port practices, as shown, for example, in (Martínez-Moya et al., 2019; Giulianetti and Sciomachen, 2024; Cai et al., 2024).

In this paper, we focus on the TP activity aimed at optimising terminal efficiency. More specifically, as an innovative aspect, we present a Mixed Integer Linear Programming model for the allocation of containers to ship positions with the aim of minimising the total distance travelled by the terminal's transport vehicles, thus considering the reduction of energy consumed for transport between the yard and the quay. This is achieved by considering that TP knows both the distance between the bays of the ship to be loaded and the different yard positions where the containers are stacked. In this way, when alternative assignments are possible, i.e., when two homogeneous containers are available for a ship position but located in different yard positions, TP selects the one that minimises the distance between the yard position and the ship bay where the container is to be stowed. In the remainder of the paper, Section 2 formally introduces the considered problem as well as the related notation. Section 3 introduces a mathematical programming model, and Section 4 provides the analysis of the proposed model for a real-life instance. Finally, Section 5 draws some conclusions.

2. Problem definition and notation

The problem considered is the detailed stowage planning faced by the TP based on the current stowage state of the container ship and the aggregate stowage plan defined by the SC for the current port. In particular, from a modeling perspective, we aim to reduce the energy consumption of trailers that transport containers between the bay and the yard. Our objective is to minimize the distance between the yard location of each export container and the dock location associated with its assigned bay. To achieve this, the following information is required:

- *the current storage composition after unloading of the import containers*, i.e., the state of the ship slots $l = (b, r, t) \in O$, where O denotes the overall set of slots locations in the ship, after the containers bound for the current port have been unloaded. Each slot is identified by three indexes b, r, t denoting, respectively, the bay, the row, and the tier. Let L represent the set of free slots; then the details of the containers currently loaded in $l \in O \setminus L$ are given, i.e., $\hat{w}_l$ (weight class), $\hat{e}_l$ (exact weight), $\hat{s}_l$ (size) and $\hat{p}_l$ (type);
- *the information for the export container to be loaded*. Let C be the set of containers to be loaded. These containers are partitioned into a set of groups G, where each group is identified by fixed destination (d_c), weight class (w_c), size (s_c), and type (p_c) of the included containers. For each export container $c \in C$, the exact weight e_c and $l_c^Y \in Y$ the location where the container is stacked in the yard are also known, with Y being the set of yard locations;
- *the aggregate stowage plan for the current port*. Let H be the set of hatch locations of the ship; for each hatch location $h \in H$, $L_h \subset L$ denotes the set of available slots in h, and $N_{g,h}$ the number of containers of group $g \in G$ assigned to hatch location h by the aggregate loading plan. Note that all groups of containers assigned to the same hatch location are characterized by the same destination due to the block stowage policy adopted by the aggregate planning;
- *the weight limits for the stability of the stacks of containers*. For each stack of slots identified by a pair $(b, r), b \in B, r \in R$, where B and R denote respectively the set of ship bays and rows, $W_{b,r}^{max}$ denotes the maximum total weight for the containers stacked in (b, r) is given.

Further sets and parameters are introduced below.

Sets

- W set of container weight classes;
- D set of dock locations associated with the bays of the ship, i.e., the locations in the docking area where quay cranes can take containers from trailers to be loaded in the different bays of the ship;
- $B^O, B^E \subset B$, respectively the sets of odd and even bays;
- T set of tiers;
- $RT_b = \{(r, t) : (b, r, t) \in L\}$ subset of pairs of rows and tiers available in each bay b, either in hold or on deck;
- $L_{h,g} \subset L, h \in H, g \in G$ subset of slots of hatch location h available for containers of class g;
- $L_{g_c} \subset L, g \in G, c \in C$ subset of ship slots available to stow container of class g_c, i.e., the class of container c;
- $A_b = \{(b, b-1, b+1), b \in B^E\}$ set of paired bays (each element associates an even bay with the two alternative odd bays);
- $C_g \subseteq C, g \in G$ subset of containers of group g;
- $C_w, w \in W$ subset of containers of the weight class w;
- $C_l \subseteq C$ or $C_{(b,r,t)} \subseteq C, l = (b, r, t) \in L$ set of containers compatible with ship slot $l = (b, r, t)$. Note that compatibility refers to (1) the destination, as assigned to the hatch h such that $l \in L_h$; (2) size, according to the size for bay b; (3) type, according to the type of containers that can be stowed in l (e.g., reefer, HC, ...);
- $C^{HC} \subset C$ subset of High Cube containers;
- $C_l^{HC}, l = (b, r, t) \in L$ subset of HC containers compatible with ship slot $l = (b, r, t)$;
- $B_c \subset B, c \in C$ subset of bays that are compatible for stowing container c.

Parameters

- $g_c = (d_c, w_c, s_c, p_c) \in G$ group of container $c \in C$;
  $\hat{e}_{(b,r,t)}, (b,r,t) \in O$ weight of the container located in slot (b,r,t), where $\hat{e}_{(b,r,t)} > 0$ for $(b,r,t) \in O \setminus L$ (not free slots), and $\hat{e}_{(b,r,t)} = 0$ for $(b,r,t) \in L$ (free slots);
- $t^{min}_{b,r}, b \in B, r \in R$ lowest available tier in stack (b,r), considering the containers that remain on board after unloading those for the current port. If the stack is empty, $t^{min}_{b,r}$ is the first tier; otherwise, it is the tier of the highest container still in the stack;
- $t^{max}_{b,r}, b \in B, r \in R$ highest available tier in the stack identified by the pair (b,r);
- $l^D_b \in D, b \in B$ dock location associated with bay b (corresponds directly to the bay index);
- $D_{l^Y_c, l^D_b}, l^Y_c \in Y, l^D_b \in D, c \in C, b \in B$ distance between the yard location of the export container c and the dock location associated with bay b;
- Π a big number.

The detailed stowage planning problem consists of assigning the export container in C to the available slots of the ship in L with the objective of minimizing the distance between the yard locations of export containers and the dock locations associated with the bays to which these containers are assigned. Furthermore, the detailed plan should comply as much as possible with the assignments specified by the aggregate stowage plan. Finally, to ensure solutions are found even in cases of infeasibility, the non-assignment of containers is heavily penalized.

3. A mathematical programming model for the detailed stowage planning

In this section, the proposed MILP model is presented, first introducing the used variables.

Variables

- $y_{b,r,t} \in \{0,1\}, (b,r,t) \in L$ binary variable denoting with value 1 the fact that slot (b,r,t) is used to stow a container;
- $x_{c,b,r,t} \in \{0,1\}, c \in C, l = (b,r,t) \in L_{g_c}$ binary variable denoting with value 1 the fact that container c of group g_c is stowed into slot $(b,r,t) \in L_{g_c}$ that, according to the SC plan, is available for group g_c;
- $z_c \in \{0,1\}, c \in C$ binary variable denoting with value 1 the fact that export container c cannot be stowed in any ship slots;
- $m_{g,h} \in \mathbb{Z}_+, g \in G, h \in H$ integer variable corresponding to difference between $N_{g,h}$ and the number of export containers of group g that are actually stowed into hatch location h.

The proposed MILP model is then the following:

$$min\ \ \Pi \cdot (\sum_{c \in C} z_c + \sum_{g \in G} \sum_{h \in H} m_{g,h}) + \sum_{c \in C} \sum_{b \in B_c} D_{l^Y_c, l^D_b} \cdot \sum_{(r,t) \in RT_b} x_{c,b,r,t} \tag{1}$$

subject to

$$\sum_{(b,r,t) \in L_{g_c}} x_{c,b,r,t} + z_c = 1 \quad c \in C \tag{2}$$

$$\sum_{c \in C_g} \sum_{(b,r,t) \in L_{h,g}} x_{c,b,r,t} - N_{g,h} \leq m_{g,h} \quad h \in H, g \in G : N_{g,h} > 0 \tag{3}$$

$$N_{g,h} - \sum_{c \in C_g} \sum_{(b,r,t) \in L_{h,g}} x_{c,b,r,t} \leq m_{g,h} \quad h \in H, g \in G : N_{g,h} > 0 \tag{4}$$

$$\sum_{c \in C_l} x_{c,b,r,t} = y_{b,r,t} \quad l = (b,r,t) \in L \tag{5}$$

$$2 \cdot y_{b,r,t} + y_{b-1,r,t} + y_{b+1,r,t} \leq 2 \quad (b, r, t) \in L, b \in B^E, (b, b-1, b+1) \in A_b \tag{6}$$

$$\begin{aligned} y_{b,r,t} &\leq y_{b,r,t-1} + \frac{1}{2}(y_{b-1,r,t-1} + y_{b+1,r,t-1}) \\ &(b, r, t) \in L : b \in B^E, t > t^{min}_{b,r}, (b, b-1, b+1) \in A_b, (b-1, r, t-1), (b+1, r, t-1) \in L \end{aligned} \tag{7}$$

$$\begin{aligned} y_{b,r,t} \leq\; & y_{b-1,r,t-1} \\ & (b, r, t) \in L : b \in B^E, t > t^{min}_{b,r}, (b, b-1, b+1) \in A_b, \\ & (b-1, r, t-1) \in L, (b+1, r, t-1) \in O \backslash L \end{aligned} \tag{8}$$

$$\begin{aligned} y_{b,r,t} \leq\; & y_{b+1,r,t-1} \\ & (b, r, t) \in L : b \in B^E, t > t^{min}_{b,r}, (b, b-1, b+1) \in A_b, \\ & (b+1, r, t-1) \in L, (b-1, r, t-1) \in O \backslash L \end{aligned} \tag{9}$$

$$y_{b,r,t} \leq y_{b,r,t-1} \quad (b, r, t), (b, r, t-1) \in L : b \in B^O, t > t^{min}_{b,r} \tag{10}$$

$$\begin{aligned} \sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq & \sum_{c \in C_{(b,r,t-1)}} e_c \cdot x_{c,b,r,t-1} + \sum_{c \in C_{(b-1,r,t-1)}} e_c \cdot x_{c,b-1,r,t-1} + \\ & + \sum_{c \in C_{(b+1,r,t-1)}} e_c \cdot x_{c,b+1,r,t-1} \\ & (b, r, t) \in L, b \in B^E, t > t^{min}_{b,r}, \\ & (b, b-1, b+1) \in A_b, (b-1, r, t-1), (b+1, r, t-1) \in L \end{aligned} \tag{11}$$

$$\sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq \hat{e}_{(b,r,t-1)} \quad (b, r, t) \in L, b \in B^E, t > t^{min}_{b,r}, (b, r, t-1) \in O \backslash L \tag{12}$$

$$\begin{aligned} & \sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq \sum_{c \in C_{(b-1,r,t-1)}} e_c \cdot x_{c,b-1,r,t-1} + \hat{e}_{(b+1,r,t-1)} \\ & (b, r, t) \in L, b \in B^E, t > t^{min}_{b,r}, (b, b-1, b+1) \in A_b, \\ & (b-1, r, t-1) \in L, (b+1, r, t-1) \in O \backslash L \end{aligned} \tag{13}$$

$$\begin{aligned} & \sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq \sum_{c \in C_{(b+1,r,t-1)}} e_c \cdot x_{c,b+1,r,t-1} + \hat{e}_{(b-1,r,t-1)} \\ & (b, r, t) \in L, b \in B^E, t > t^{min}_{b,r}, (b, b-1, b+1) \in A_b, \\ & (b-1, r, t-1) \in O \backslash L, (b+1, r, t-1) \in L \end{aligned} \tag{14}$$

$$\sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq \sum_{c \in C_{(b,r,t-1)}} e_c \cdot x_{c,b,r,t-1} \quad (b, r, t) \in L, b \in B^O, t > t^{min}_{b,r}, (b, r, t-1) \in L \tag{15}$$

$$\sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq \hat{e}_{(b,r,t-1)} \quad (b, r, t) \in L, b \in B^O, t > t^{min}_{b,r}, (b, r, t-1) \in O \backslash L \tag{16}$$

$$\sum_{(b,r,t) \in L} \sum_{c \in C_{(b,r,t)}} e_c \cdot x_{c,b,r,t} \leq W^{max}_{b,r} \quad b \in B, r \in R : \exists (b, r, t) \in L \tag{17}$$

$$\sum_{c\in C_w} x_{c,b-1,r,t} \geq y_{b-1,r,t} + y_{b+1,r,t} + \sum_{c\in C_w} x_{c,b+1,r,t} - 2 \quad w \in W, b \in B^E, (b,r,t) \in L \tag{18}$$

$$\sum_{c\in C_w} x_{c,b+1,r,t} \geq y_{b-1,r,t} + y_{b+1,r,t} + \sum_{c\in C_w} x_{c,b-1,r,t} - 2 \quad w \in W, b \in B^E, (b,r,t) \in L \tag{19}$$

$$\sum_{c\in C_{\hat{w}}} x_{c,b+1,r,t} = y_{b+1,r,t} \quad b \in B^E, (b+1,r,t) \in L, (b-1,r,t) \in O\backslash L \tag{20}$$

$$\sum_{c\in C_{\hat{w}}} x_{c,b-1,r,t} = y_{b-1,r,t} \quad b \in B^E, (b-1,r,t) \in L, (b+1,r,t) \in O\backslash L \tag{21}$$

$$\begin{aligned} & y_{b,r,t} \in \{0,1\}, (b,r,t) \in L \\ & x_{c,b,r,t} \in \{0,1\}, c \in C, (b,r,t) \in L \\ & z_c \in \{0,1\}, c \in C \\ & m_{g,h} \in \mathbb{Z}_+, g \in G, h \in H \end{aligned} \tag{22}$$

The objective function (1) includes two main components. The first aims to minimize the deviation of the detailed plan from the given aggregated plan. In particular, it minimizes the number of unassigned containers and the sum of the differences between the number of containers of the distinct groups assigned to the hatch locations by the aggregated plan and the number of containers actually assigned. This first objective component is multiplied by a large positive coefficient Π to model its lexicographic priority. Then, the second objective component in (1) includes the sum of the total estimated distance to be covered for transporting the containers from their locations in the yard to the dock corresponding to the ship bay where they are stowed. Having assumed that containers are moved by a homogeneous fleet of vehicles with a constant speed, this component can be considered a proxy for energy consumption. Constraints (2) model demand satisfaction. They impose that all export containers must be assigned to an available ship slot. These constraints are modeled as soft constraints, since if a feasible solution loading all containers cannot be found, the number of constraints violations (i.e., containers not loaded for which $z_c = 1$) is minimized. Constraints (3) and (4) impose in a soft way that the total number of containers of class g assigned to hatch location h must be equal to $N_{g,h}$, i.e., the value given by the aggregate loading plan. The two constraints define $m_{g,h}$ as the maximum absolute deviation that is minimized. Constraints (5) state that if an available slot is used, then a container must be assigned to that slot. Constraints (6) impose the mutually exclusive use of the available slots in even bays or in the corresponding paired odd bays: if there is an available slot in an even bay, either this slot or one or both of the two slots in the corresponding odd bays can be used alternatively. Constraints (7)-(9) allow a correct stack formation in even bays: an available slot in an even bay can be used if, in the lower tier, either the slot in the same bay or the two paired slots in the corresponding odd bays are also used. The constraints (7) consider the case where in the lower tier, the slot in the even bay b is free (so the two paired odd slot $b-1$ and $b+1$ are also free), then either the 40' slot or the two paired 20' slots in the odd bays must be used; if instead only one of the two odd bay slots $b-1$ and $b+1$ is free but the other one is already assigned to a 20' container, then such free 20' slot must be used (8), (9). Therefore, configurations where a 40' container can be placed on top of two 20' containers are allowed, but not the reverse. Similarly, constraints (10) impose the correct stack formation for odd bays: an available slot in an odd bay can be used if the corresponding slot in the same bay in the lower tier is also used. Constraints (11)-(16) establish the correct weight composition in stacks, i.e., the requirement that the containers in stacks must have non-increasing weight from the lowest to the highest tier. Due to (11), a 40' container c with weight e_c can be assigned to an available even bay b at a tier higher than tier $t^{min}_{b,r}$, if, in the same bay in the lower tier, either a 40' container with weight not less than e_c is assigned, or if there are two 20' containers in the two paired odd bays $b-1$ and $b+1$, and the sum of the weights of such two 20' containers is not less than e_c. Note that these containers in the lower tier can be either export containers in C or containers already in the ship, i.e., not unloaded at the present port. Constraints (11) model the case when the slots in the lower tier are free; (12) when the lower tier in b is already occupied by a 40' container with known weight $\hat{e}_{(b,r,t-1)}$, and (13) and (14) the cases when only one of the 20' slots in bays $b-1$ and $b+1$ is free and the other one is already occupied by a container with known weight. A 20' container c with weight e_c can be stowed in an available slot in an odd bay at a tier higher than tier $t^{min}_{b,r}$ only if the corresponding slot in the odd bay in the lower tier is assigned to a container whose weight is not smaller thane_c. Constraints (15) consider the case when the slot in the lower tier is free, whereas (16) when such slot is already occupied by a 20' container with a known weight. The maximum total weight of each stack, identified by a pair (b, r), is imposed by (17). The compatibility of containers in paired 20' slots is guaranteed only if two 20' containers stowed in two paired odd slots (i.e., $b-1$ and $b+1$ for an even bay b) belong to the same weight class. Constraints (18) and (19) address the case in which both the 20' slots in bays $b-1$ and $b+1$ are free. Constraints (20) and (21) the cases when one of the two 20' slots is already occupied by a container of class of weight $\hat{w}$ (in these cases if a container is assigned to the free slot it must be one of the same class of weight). Finally, (22) defines the decision variables.

4. Experimental Results on Real Instances

Computational experiments were carried out on a real-world instance comprising 329 export containers. The MILP formulation was coded in Python and solved via IBM CPLEX 22.1.1. All runs were performed on a Windows Server system equipped with an Intel® Xeon® Silver 4314 CPU (2.40 GHz, 16 cores). In this realistic instance, our MILP (21567 constraints, 1108567 variables) achieves proven optimality in 349 s, with only six block-plan deviations and zero unassigned containers.

$\Pi = 10\,000$,

Overall objective:

$$68\,900.4 + 10\,000 \times 6 = 80\,900.4.$$

From raw container data, the information associated with each container includes size, type, weight class, origin yard, and destination demand. The solver builds a binary assignment model that maps every container to a feasible ship slot. The solver incorporates yard-to-bay distances and capacity limits, enforces group-and-hatch loading requirements, and minimizes total transport plus penalty costs. Running CPLEX on model(1)-(22), we obtain the bay-row-tier assignments in the detailed storage plan.

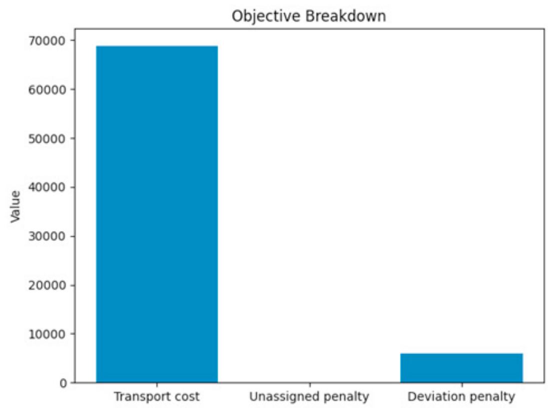

Fig. 1. Objective breakdown: transport cost vs. deviation penalty.

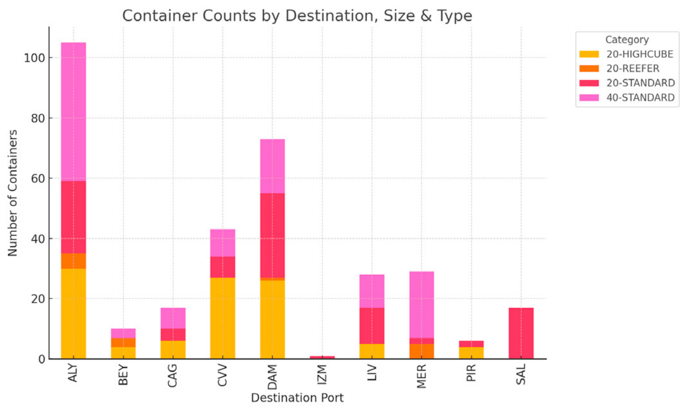

Fig. 2. Number of containers assigned per group.

Figure 1 illustrates the breakdown of the final objective into transport cost and deviation penalty. Figure 2 shows the 329 containers, with IDs from 4 to 332, characterized by their physical size, structural type, weight class, and destination. Of these, 213 are 20-foot and 116 are 40-foot units; 213 are standard types, 102 are high-cube variants, and 14 are reefers; finally, their shipments are bound for a range of destinations led by ALY (105 containers), DAM (73), CVV (43), MER (29) and LIV (28), with smaller numbers to other ports. This mix of sizes, types, and weights in diverse destinations underpins the planning of yard placement, slot assignment, and loading strategies.

The lexicographic penalty scheme successfully trades minimal slot-plan deviations for substantial reductions in trailer travel distance. These preliminary results encourage us to carry out a more extensive experimental analysis of this model in the near future, with the aim of assessing its full potential and identifying possible limitations.

5. Conclusions

This study presents a detailed stowage planning model that achieves a global optimal solution for a real size ship of about 4,500 TEUs in an acceptable computation time. The approach allocates each container while minimizing yard-to-dock movements, also penalizing changes with respect to the reference aggregate stowage plan. This objective can be considered a proxy for the minimization of energy consumption since we assumed a homogeneous fleet of vehicles for container handling and a constant vehicle speed. As a future research direction, we also plan to consider non-homogeneous fleets. Other future extensions will be devoted to the design of a heuristic approach capable of dealing with larger-sized container ships.

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