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Optimizing Port Terminal Vehicle Scheduling for Containership Berth Operations

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Abstract

This paper presents a mixed-integer linear programming (MILP) model for scheduling container handling activities at maritime terminals. The model coordinates the assignment and sequencing of trailers and reach stackers for both import and export containers, synchronizing the vehicles' operation to minimize waiting time. Computational experiments show that the model generates optimal schedules across various instance sizes. While small and medium instances are solved within a reasonable amount of time, larger instances exhibit increased computation time due to the problem's combinatorial complexity. These results validate the model as a reliable foundation for vehicle scheduling in terminal environments and emphasize the need for more scalable solution approaches.

Keywords: Container terminal; vehicle routing and scheduling; Mixed integer linear program

1. Introduction and Literature review

Optimal management of the various equipment available in the berthing and yard areas of a container terminal, in particular quay cranes and transport equipment, such as tractors and reach stackers, is crucial to improving the efficiency of the service provided by the terminal to the containerships. The need to optimize container handling operations within a terminal has become even more necessary since the beginning of the 2000s, when the first mega containerships began to circulate (Ambrosino and Sciomachen, 2003; Steenken et al., 2004). Between the various critical aspects associated with the handling activities, container terminal vehicle scheduling represents a challenging area of research within maritime logistics, as it directly influences not only its operational efficiency, but also vessel turnaround time, and overall terminal capacity (Bierwirth and Meisel, 2015). In this direction, the present work lays the groundwork for the design of a decision support system (DSS) for the planning of the operations of the available means of transport to increase the efficiency of the terminal, i.e. to minimize the time needed to complete the unloading/loading operations of the ships and to decrease the costs related to transport. This objective is pursued by trying to

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synchronize as much as possible the chain of operations carried out by the different equipment, i.e. by minimizing the waiting time between the completion of one operation and the start of the next. The minimization of the delay time is also addressed in (Zhong et al., 2020), where the authors combine path planning and scheduling to define conflict-free path planning of multi-AGVs to minimize their delay time.

Over the past two decades, the literature concerning scheduling within maritime terminals has evolved from isolated studies on specific problems, such as truck dispatching or yard crane deployment, to more integrated approaches that address berth allocation, quay crane scheduling, and yard operations simultaneously (Liang et al., 2009; Liu et al., 2015; Karam and Eltawil, 2015; Jin et al., 2017). In parallel, there has been a shift towards robust and dynamic methods, with the aim of managing the frequent uncertainties arising from weather conditions, demand fluctuations and mooring delays (Xu et al., 2022; Wang et al., 2024). Foundational research typically examined single-resource scheduling, focusing on either vehicles or cranes independently (Kim and Bae, 1998). These studies adopted mathematical programming techniques, such as Mixed Integer Linear Programming (MILP), to derive optimal or near-optimal solutions. An exact solution approach for scheduling the handling activities of cooperative gantry cranes is proposed in (Kress et al., 2019). Although successful for small instances, these methods suffer from scalability issues when applied to larger real-world problems (Steenken et al., 2004). To address computational complexity, several authors introduced metaheuristics, including genetic algorithms, tabu search, and simulated annealing, which demonstrated improvements in solution quality and run-time (Chen and Langevin, 2011). Subsequent works moved toward integrated scheduling, incorporating berth allocation and resource assignment into the vehicle dispatch process for a more holistic solution (Iris et al., 2015). Multi-objective formulations have become increasingly prevalent, considering factors such as total operational costs, makespan, and environmental impact. In (Homayouni and Tang, 2013) a MILP model and a genetic algorithm are proposed to optimize the coordinated scheduling of cranes and automated guided vehicles in container terminals by minimizing the total traveling time of the vehicles and delays of cranes. In (Hong et al., 2023) an integrated scheduling approach is proposed that coordinates double-trolley quay cranes with driverless electric trucks to synchronize loading and unloading operations and achieve minimal overall energy consumption. Note that, as recognized in planning manufacturing operations (e.g., in (Paolucci et al., 2017)), improving environmental sustainability in container terminal activities requires to consider the energy consumption due to the operations performed by the involved means of transport. In particular, quantifying and reducing CO_2 emissions from key terminal equipment has proven crucial to advancing green port initiatives (Martínez-Moya et al., 2019). In tandem with optimization-focused research, simulation-based studies assess policy decisions' impacts on system performance under various uncertainty scenarios (Dragović et al., 2017), often incorporating agent-based architectures to capture the complexity and heterogeneity of terminal actors to provide insights into how vehicle scheduling policies might perform in practice. between dock and yard.

As a novel issue, this paper focuses on a Vehicle Scheduling Optimization Model (VSOM) which exploits an optimization approach for scheduling the activities of the means of transport used for transferring containers from/to the yard-berth areas, with the aim of improving their synchronization to minimize waiting time. In particular, the present synchronization problem is modeled as scheduling a set of jobs associated with the requests for moving both import and export containers. The remainder of the paper is organized as follows. Section 2 presents in detail the problem under study, while the related mathematical model is presented in Section 3. Section 4 reports the computational results, and conclusions are given in Section 5.

2. Problem statement and notation

The considered Container Terminal Vehicle Scheduling Problem (CTVSP) consists of determining the optimal plan for the available means of transport in a port terminal to move containers from a vessel to the yards and vice versa. In particular, the optimization consists in synchronizing the movements of the containers between the ship and the yards so that the waiting times between the operations performed by the different means are minimized. We assume that the vessel is operated by a given number of quay cranes for unloading the containers bounded for the port and then loading the containers departing from it. For each quay crane assigned to the vessel, the sequence of containers to be first unloaded and then loaded is given. Each container is characterized by a set of information as destination, weight, size (20", 40"), type (standard, reefer, dangerous, etc.). The movement of the containers between the quay area and the yard is performed by trailers and reach stackers. A number of trailers is assigned to the quay area or crane. Quay cranes unload containers on trailers only; quay cranes load the containers picking them up exclusively from trailers.

The pick up operations of containers from the yard are performed by reach stackers. The available reach stackers are assigned to different areas of the yard. We assume that the travel time needed to move between the positions in the port area interested by the import and export operations is known a priori and fixed.

3. A mathematical model

The CTVSP can be modeled as a scheduling problem for a set of jobs, each requiring three operations $O = \{1, 2, 3\}$ performed by three different terminal equipment. Specifically, the import and export processes are modeled as follows:

Import:

1. an import container c is unloaded by a given quay crane q from a ship s taking an amount of time T^U (initially considered independent from the container position, for the sake of simplicity) assumed fixed;
2. the unloading operation moves c in a location, called origin location for the container, i.e., the starting location for operation 2 denoted as $l^S_{2,c}$, on the quay below the quay crane q; a trailer r must be present at location $l^S_{2,c}$ to take the unloaded container c and then to move it to a yard location, called destination location for the container, i.e., the final location for operation 2 denoted as $l^F_{2,c}$, that is close to the yard final position of the container; the time needed for the transport, $T_{l^S_{2,c}, l^F_{2,c}}$, depends on the origin and destination locations;
3. a reach stacker k should be available at destination $l^F_{2,c} = l^S_{3,c}$ (i.e., the starting location for operation 3), to unload the container from the trailer, so minimizing the trailer waiting time, and to move the container to its final position on a stack in the yard; the time needed for this movement, T^S is assumed initially fixed.

Export:

1. an export container c is taken from its position in a stack of a yard by a reach stacker k; the reach stacker starts this operation when a trailer is available to receive the container at the container starting location for operation 2, $l^S_{2,c}$, that for export is close to the position of the container in the yard; the operation is completed when the reach stacker loads the container on the trailer; this operation takes an amount of time T^T assumed initially fixed;
2. the trailer then moves the container c from location $l^S_{2,c}$ to the destination location $l^F_{2,c}$, that for export is on the quay below a given quay crane q in charge of loading the container on its ship s; the time needed for the transport, $T_{l^S_{2,c}, l^F_{2,c}}$, depends on the origin and destination locations;
3. the trailer possibly waits for the quay crane starting the last operation 3: the quay crane unloads the container from the trailer and then loads it into the ship; the time needed for this operation, T^L is assumed initially fixed.

In the proposed scheduling problem the decision concerns the definition of the assignment and sequencing of trailers and reach stackers to minimize container handling delays. Then, decision variables include the binary assignments (y^R, y^K), operation start and completion times (t^S, t^C), and sequencing (x^R, x^K). These are interrelated through temporal and resource-based constraints ensuring proper synchronization.
The problem is associated with a directed graph $G = (V, A)$, where $V = L \cup L^R_0 \cup L^K_0$ is the set of nodes associated with location, and the set $A = A^R \cup A^K$ includes the arcs that can be feasibly traveled by the trailers, i.e., $A^R = \{(i, j) : \exists r \in R, i, j \in L^R_r\}$, and the arcs that can be feasibly traversed by the reach stackers, i.e., $A^K = \{(i, j) : \exists k \in K, i, j \in L^K_k\}$. From this graph the data related to the possible movement of trailers and reach stackers and their transportation times can be obtained. Hence the data for the scheduling problem are obtained from the set of information described in the following.

Sets

- S set of container ships;
- Q set of quay cranes;
- $Q_s \subseteq Q$, $s \in S$ subset of quay cranes assigned to unload and load ship s;
- C set of containers;
- $C^I \subseteq C$ subset of import containers;

- $C^E \subseteq C$ subset of export containers;
- $C^I_q, q \in Q_s, s \in S$ set of import containers arrived with ship s that are unloaded by quay crane q;
- $C^E_q, q \in Q_s, s \in S$ set of export containers departing with ship s that are loaded by quay crane q;
- $I_q = (c_{q,h}, h = 1, \ldots, n_q), q \in Q_s$ unloading sequence of import containers for quay crane q; container $c_{q,i}$ in the i-th position is denoted as $I_q[i]$, for $q \in Q$;
- $E_q = (c_{q,h}, h = 1, \ldots, m_q), q \in Q_s$ loading sequence of export containers for quay crane q; container $c_{q,i}$ in the i-th position is denoted as $E_q[i]$, for $q \in Q$;
- L set of locations;
- R set of trailers;
- K set of reach stackers;
- $L^R_0 = \{l_{0,r} : r \in R\}$ set of initial locations for the trailers;
- $L^K_0 = \{l_{0,k} : k \in K\}$ set of initial locations for the reach stackers;
- $L^R_r \subseteq L, r \in R$ subset of locations that can be visited by trailer r;
- $L^K_k \subseteq L, k \in K$ subset of locations that can be visited by reach stacker k;
- $R^I_c \subseteq R, c \in C^I$ subset of trailers available to move the import containers;
- $K^I_c \subseteq K, c \in C^I$ subset of reach stackers available to stack the import containers in its final position in yard;
- $R^E_c \subseteq R, c \in C^E$ subset of trailers available to move the export containers;
- $K^E_c \subseteq K, c \in C^E$ subset of reach stackers available to take the export containers from their positions in the yard;
- $R_c \subseteq R, c \in C$ subset of trailers available for container c; either $R_c = R^E_c$ if $c \in C^E$ or $R_c = R^I_c$ if $c \in C^I$;
- $K_c \subseteq K, c \in C$ subset of reach stackers available for container c; either $K_c = K^E_c$ if $c \in C^E$ or $K_c = K^I_c$ if $c \in C^I$;
- $O = \{1, 2, 3\}$ set of container operations; for import, operation 1 is performed by the assigned quay crane, operation 2 by a trailer and operation 3 by a reach stacker. The association is reversed for export.

Parameters

- $rd^S_s = rd^Q_q \geq 0, q \in Q_s, s \in S$ release date of ship s, which corresponds to the earliest time instant at which all the quay cranes assigned to the ship can start unloading the import containers;
- $T_{a,b}, a, b \in L$ the transportation time from location a to location b;
- $l^S_{o,c}, o \in O, c \in C$ starting location for operation o of container c;
- $l^F_{o,c}, o \in O, c \in C$ final location for operation o of container c;
- T^U the time needed by quay cranes to unload a container from a ship (it includes the time needed to reach the container, keep it and move it onto a trailer);
- T^L the time needed by quay cranes to load a container on a ship;
- T^S the time needed by a reach stacker to unload a container from a trailer and stack it in the yard;
- T^T the time needed by a reach stacker to unstack a container from the yard and load it on a trailer;
- $0, N$ two fictitious operations, respectively the first one and last one, for trailers and reach stackers.
- M large penalty constant used to discourage leaving containers unhandled.

The CTVSP can be modeled as a job shop in which each job is associated with an import or export container, and it requires three operations performed by three types of machines (quay cranes, trailers and reach stackers). The assignment of the jobs to the quay cranes is given and the operations of the quay cranes must be performed one after the other without delay. In general there are alternative trailers and reach stackers to perform the other two operations of the jobs. The mathematical model of the problem here follows.

Variables

- $y^R_{c,r} \in \{0, 1\},\ c \in C,\ r \in R_c$: binary job–trailer assignment variable, where R_c is equal to either R^I_c or R^E_c depending on whether c is an import or export container;
- $y^K_{c,k} \in \{0, 1\},\ c \in C,\ k \in K_c$: binary job–reach stacker assignment variable, where K_c is equal to either K^I_c or K^E_c depending on whether c is an import or export container;
- $Z_c \in \{0, 1\},\ c \in C$: binary variable equal to 1 if container c is not handled and 0 otherwise;

- $t^C_{o,c} \geq 0,\ o \in O,\ c \in C$: completion time of operation o for container c; for import containers, $t^C_{1,c}$ is the completion time of the unloading operation so the container is ready to be loaded onto a trailer;
- $t^S_{o,c} \geq 0,\ o \in O,\ c \in C$: start time of operation o for container c;
- $w_{o,c} \geq 0,\ o = 1, 2,\ c \in C$: waiting time after equipment completes operation o for container c before the next equipment begins operation $o + 1$; e.g., if $o = 1$ and c is an import container, $w_{1,c}$ is the waiting time of the quay crane after unloading container c from the ship, before a trailer receives c and starts operation 2;
- $x^R_{i,j,r} \in \{0, 1\},\ i \in C \cup \{0\}, j \in C \cup \{N\},\ i \neq j,\ r \in R_i \cap R_j$: binary trailer sequencing variables such that $x^R_{i,j,r} = 1$ if container i is moved by trailer r immediately before container j; otherwise $x^R_{i,j,r} = 0$;
- $x^K_{i,j,k} \in \{0, 1\},\ i \in C \cup \{0\}, j \in C \cup \{N\},\ i \neq j,\ k \in K_i \cap K_j$: binary reach stacker sequencing variables such that $x^K_{i,j,k} = 1$ if container i is moved by reach stacker k immediately before container j; otherwise $x^K_{i,j,k} = 0$.

Objective function:

$$\min\left(\sum_{c\in C}(w_{1c} + w_{2c}) + M\sum_{c\in C} Z_c\right) \tag{1}$$

subject to

$$\sum_{r\in R_c} y^R_{c,r} + Z_c = 1 \quad c \in C \tag{2}$$

$$\sum_{k\in K_c} y^K_{c,k} + Z_c = 1 \quad c \in C \tag{3}$$

$$\sum_{j\in C} x^R_{0,j,r} \leq 1 \quad r \in R_c \tag{4}$$

$$\sum_{j\in C} x^K_{0,j,k} \leq 1 \quad k \in K \tag{5}$$

$$\sum_{\substack{i\in C\cup\{0\}\\ i\neq c}} x^R_{i,c,r} = y^R_{c,r} \quad c \in C, r \in R_c \tag{6}$$

$$\sum_{\substack{j\in C\cup\{N\}\\ j\neq c}} x^R_{c,j,r} = y^R_{c,r} \quad c \in C, r \in R \tag{7}$$

$$\sum_{\substack{i\in C\cup\{0\}\\ i\neq c}} x^K_{i,c,k} = y^K_{c,k} \quad c \in C, k \in K_c \tag{8}$$

$$\sum_{\substack{j\in C\cup\{N\}\\ j\neq c}} x^K_{c,j,k} = y^K_{c,k} \quad c \in C, k \in K_c \tag{9}$$

$$\sum_{j\in C} x^R_{0,j,r} = \sum_{i\in C} x^R_{i,N,r} \quad r \in R \tag{10}$$

$$\sum_{j\in C} x^K_{0,j,k} = \sum_{i\in C} x^K_{i,N,k} \quad k \in K \tag{11}$$

$$t^S_{1,I_q[1]} \geq rd^Q_q \quad q \in Q \tag{12}$$

$$t^C_{1,I_q[h]} = t^S_{1,I_q[h]} + T^U(1 - Z_c) + w_{1,I_q[h]} \quad q \in Q, h = 1, \ldots, n_q \tag{13}$$

$$t^S_{2,c} \geq t^C_{1,c} \quad c \in C \tag{14}$$

$$t^C_{2,c} = t^S_{2,c} + T_{l^S_{2,c}, l^F_{2,c}}(1 - Z_c) + w_{2,c} \quad c \in C \tag{15}$$

$$t^S_{3,c} \geq t^C_{2,c} \quad c \in C \tag{16}$$

$$t^C_{3,c} = t^S_{3,c} + T^S(1 - Z_c) \quad c \in C^I \tag{17}$$

$$t^C_{3,c} = t^S_{3,c} + T^L(1 - Z_c) \quad c \in C^E \tag{18}$$

$$t^C_{1,c} = t^S_{1,c} + T^T(1 - Z_c) + w_{1,c} \quad c \in C^E \tag{19}$$

$$t^C_{3,E_q[h]} \geq t^C_{3,E_q[h-1]} \quad q \in Q, h = 2, \ldots, m_q \tag{20}$$

$$t^S_{3,E_q[1]} \geq t^C_{1,Iq[nq]} \quad q \in Q \tag{21}$$

$$t^S_{2,j} \geq t^C_{2,i} + T_{l^F_{2,i}, l^S_{2,j}} - T^{max}(1 - x^R_{i,j,r}) \quad i, j \in C, i \neq j, r \in R_i \cap R_j \tag{22}$$

$$t^S_{2,j} \geq T_{l_{0,r}, l^S_{2,j}} - T^{max}(1 - x^R_{0,j,r}) \quad j \in C, r \in R_j \tag{23}$$

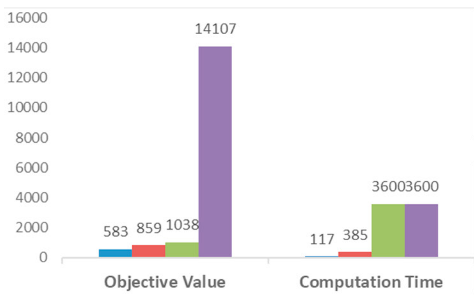
$$t^S_{o,j} \geq t^C_{o',i} + T_{l^F_{o',i}, l^S_{o,j}} - T^{max}(1 - x^K_{i,j,k}) \quad o, o' \in \{1, 3\}, i, j \in C, i \neq j, k \in K_i \cap K_j \tag{24}$$

$$t^S_{o,j} \geq T_{l_{0,ik}, l^S_{o,j}} - T^{max}(1 - x^K_{0,j,k}) \quad o \in \{1, 3\}, j \in C, k \in K_i \cap K_j \tag{25}$$

$$\begin{aligned} &x^R_{i,j,r} \leq 1 - Z_i \quad i, j \in C,\ i \neq j,\ r \in R_i \cap R_j \\ &x^K_{i,j,r} \leq 1 - Z_j \quad i, j \in C,\ i \neq j,\ r \in K_i \cap K_j \\ &w_{o,c} \leq T^{max}(1 - Z_c) \quad o = 1, 2, c \in C \end{aligned} \tag{26}$$

$$\begin{aligned} &y^R_{c,r} \in \{0, 1\}, c \in C, r \in R_c \\ &y^K_{c,k} \in \{0, 1\}, c \in C, k \in K_c \\ &t^C_{o,c} \geq 0, o \in O, c \in C \\ &t^S_{o,c} \geq 0, o \in O, c \in C \\ &w_{o,c} \geq 0, o = 1, 2, c \in C \\ &x^R_{i,j,r} \in \{0, 1\}, i, j \in C, i \neq j, r \in R_i \cap R_j \\ &x^K_{i,j,k} \in \{0, 1\}, i, j \in C, i \neq j, r \in K_i \cap K_j \end{aligned} \tag{27}$$

Objective (1) has two components, the first one aims at minimizing the total waiting time of the quay cranes and trailers, while the second includes a penalty term to discourage leaving containers unhandled. Constraints (2) and (3) impose that each container is assigned to a single trailer and a single reach stacker, respectively, to perform the related operations or is unhandled. Constraints (4) and (5) state that for each trailer and reach stacker, respectively, there is at most a single starting container performing its related operation. Constraints (6) - (9) establish that if a container is assigned to a trailer (constraints (6) and (7)) or a reach stacker (constraints (8) and (9)), then the operation related to such a container must be preceded by an operation for another container or it is the first one performed by the trailer or reach stacker. Equations (10) and (11) are the flow conservation conditions imposing that if a trailer or a reach stacker is used to perform a first operation, it must also have an operation that is performed as last one. Constraints (12) set the start time of the first operation that starts the unloading of import containers by quay cranes q not smaller than the ready time for such crane. Equations (13) provide the sequence of unloading the import containers $c \in C^I$ for quay cranes. In particular, the completion time of operation 1 for an import container c corresponds to unload the container and load it on a trailer, possibly waiting for it, if variables $w_{1,c}$ (that here is the time the quay crane waits for the arrival of trailer) assume a positive value. Constraints (14) and (15) determine, respectively, the starting and completion time of operation 2 performed on any container. In fact, operation 2 is always the intermediate task performed by trailer both on import and export containers. In particular, (14) impose that a trailer starts operation 2 on a container as soon as a quay crane for import or a reach stacker for export has loaded it on the trailer. Then (15) compute the completion time of operation 2 for a container adding to the related start time the travel time between the starting and ending location for the operation, considering a possible waiting time $w_{2,c}$ that for import corresponds to the arrival of a reach stacker and for export that of the quay crane. Note that this completion time includes the time needed to unload the container from the trailer that is hence ready for its next operation. The successive operation 3 then can start exactly at the completion of operation 2, since the completion includes the possible waiting time (16). For import containers, equations (17) determine the completion time of operation 3 adding to the related start time, the time needed by the reach stacker to stack the container in the yard, whereas for export container (18) compute the completion times adding the time needed by the quay crane to load the container on the ship. Considering the export container, equations (19) compute the completion time of operation 1 performed by reach stacker adding to the start time the time needed to retrieve the container from the stack in the yard and to load it on a trailer, possibly waiting a time $w_{1,c}$ for the arrival of this latter. The following inequalities (20) impose that the loading sequence of the quay cranes for the export containers is satisfied. In addition, (21) impose that for each quay crane the first loading operation for an export container occurs after the completion of the unloading sequence for the import containers. Constraints (22) provide the sequencing conditions for the trailers, i.e., for operations 2 assigned to each trailer, and (23) is the special case for the first operation performed by trailers. Similarly (24) do the same for the reach stacker that are in charge of performing operation 3 for import containers and operation 1 for export containers, and (25) hold for the first operations of reach stackers. Variable upper bound constraints (26) set to zero both sequencing and waiting time variables for not handled containers. Finally, constraints (27) provide the definition of the decision variables.



	Containers	Trailers	Reach Stackers	Objective Value	Computation Time
1	20	4	4	583	117
2	40	4	4	859	385
3	50	4	4	1038	3600
4	70	4	4	14107	3600

Fig. 1. Results for Selected Instances

4. Results and Discussion

This section summarizes the model's performance on four benchmark instances of increasing scale and operational complexity. All instances involve three quay cranes and identical equipment (four trailers and four reach stackers), but differ in the number of containers and layout density, as shown in Figure 1. The smaller instances with 20 and 40 containers were solved to optimality in 117 and 385 seconds, achieving objective values of 583 and 859, respectively.

The larger instances, with 50 and 70 containers, reached the time limit of 3600 seconds, but yielded feasible solutions with objective values of 1038 and 14107. Although optimality was not proven for larger instance cases, the model provided high-quality solutions under tight resource constraints. These preliminary results confirm the robustness and practical value of the model in a range of terminal scenarios. The increased solve time and objective values in larger instances point to the need for scalable strategies such as matheuristics or metaheuristics. All experiments were run in Python using Gurobi 11.0.3 on a Windows server with an Intel(R) Xeon(R) Silver 4314 CPU (2.40 GHz, 16 cores), with a two-hour time limit per run. Future work will expand this preliminary computational analysis and explore improvements to support large-scale, time-sensitive applications.

5. Conclusion and Future Work

This study presented a MILP model for vehicle scheduling in container terminals, capable of generating feasible and optimal solutions across a range of instance sizes. The results validate the model's effectiveness, particularly in small and medium-scale problems, while also highlighting increased computational demand as problem size grows primarily due to the number of containers and locations involved. To improve scalability, future research will focus on the integration of matheuristic and metaheuristic strategies. These approaches aim to retain the accuracy of the MILP model while enabling faster, more adaptive solutions for large-scale or real-time operational scenarios.

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