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ORIGINAL ARTICLE

Priority rules for handling containers to improve energy consumption and terminal efficiency

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Abstract

This paper addresses the optimization of the yard crane handling processes in a container terminal to reduce energy consumption and improve overall system performance. More precisely, the paper presents and evaluates different sequencing rules, based on predefined priorities, to organize the rail yard to minimize moves during the rail loading operations. The minimization of overall energy consumption and maximum tardiness are considered, simultaneously assessing these two components of the objective function to better understand how they interact and how they can be optimized together. As a novel issue in optimization, a hill climbing algorithm is implemented, searching for the yard configuration that most improves the efficiency of container handling while being able to integrate different management rules of the terminal. The reference case study is the PSA Pra terminal in Genoa, Italy. A full rail yard with known delivery times, and crane operating along a single stack, is the operative scenario. Random due time sequences are generated during test instances, while technical data of crane are used. Moreover, crane movements involve both loading and unloading along multiple axes. From the results, the best priority rules improve energy consumption and lateness of the initial configuration of the yard by up to 55%, thus allowing the terminal management to reorganize the storage areas accordingly and improve their efficiency. The proposed priority rules bridge the gap between theoretical optimization procedures and container terminal practices.

Keywords Container terminal · Handling operations · Yard crane · Sequencing rules · Energy consumption · Hill climbing heuristic

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1 Introduction

Since the beginning of this millennium, two phenomena have significantly characterized maritime transport. The first is the rate of growth in containership sizes, such that ships of the later generation can load in excess of 24,000 TEU. The second development is the considerable focus on environmental sustainability in the transport sector, and particularly in the maritime one, which obliges both shipping companies and terminal operators to pay more attention to their fuel and energy consumption. Both phenomena, have resulted in several infrastructural adjustments in ports and their information systems, which are necessary to ensure acceptable performance in cargo handling operations and adequate service levels, as well as to handle peak port congestion and environmental issues (Haralambides 2019). For this reason, from the last two decades operations research and decision science methods are increasingly being used to improve the efficiency and productivity of container terminals, as required by today's shipping markets (Steenken et al. 2004; Carlo et al. 2014; Notteboom and Rodrigue 2008).

In the present paper, unlike cases found in literature, an innovative approach is presented to minimize both energy consumption and lateness of container handling by a yard crane. Instead of adhering to a single sequencing rule, our aim here is to explore the effectiveness of various priority ones for the crane. These rules are subsequently optimized through the implementation of a hill climbing local search algorithm. The optimization phase searches for the solution that minimizes both energy consumption and delays by varying the configuration of containers in the yard. Note that the optimal configuration of the yard, in relation to the initial one, is calculated for all the different container handling rules provided by the terminal operator, which are integrated into the proposed procedure.

In this study, carried out within the RAISE Project, spoke 4 "Smart and Sustainable Ports," at the University of Genoa, we used terminal data obtained from the website of PSA Pra terminal in Genoa (Port of Genoa 2024). Different yard scenarios are considered in the test instances. For the computation of energy consumption and timing, a flexible and adaptable code is developed, capable of accommodating different types of cranes and yards.

To facilitate understanding of our work, the remaining structure of the paper is as follows. Section 2 reports a brief overview of the literature in this area. Section 3 presents the proposed priority rules for the crane and illustrates them in detail. The main procedures implemented in the hill climbing algorithm are described in Sect. 4. The mathematical formulation of the optimization problem together with the required notation are reported in Appendix 1. Section 5 reports the computational experimentations, while conclusions are presented in Sect. 6.

2 Literature review

In the present work we deal with the yard areas of a container terminal, focusing on the sequence of containers to be unloaded from their stacks to make incoming train loading operations more efficient. An optimized yard arrangement reduces empty moves, thus reducing the energy consumption of the cranes. Storing containers in the yard and scheduling the handling operations for incoming shipping or inland forwarding are related problems in marine terminals (Ambrosino and Sciomachen 2003; Liu et al. 2019). Moreover, previous studies have shown how relevant is the yard organization to minimize unproductive moves in train loading processes. The research proposed by Corry and Kozan (2006) focuses on optimizing operational strategies in intermodal terminals, proposing an analytical tool for planning the loading of container trains. Pap et al. (2012) analyze the crane scheduling for the reloading of containers from/to trains at inland intermodal terminals using a branch and bound method.

In the context of research on logistics operations planning, several studies have focused on port and railways. Among these, (Kress et al. 2019) examines the scheduling of gantry cranes of a storage block; advanced dynamic programming and beam search algorithms are proposed to optimize the complex container handling operations. Xiyu et al. (2019) studies crane scheduling in railway transshipment areas, through an innovative decomposition approach; an algorithm is developed to minimize train residence time, enhancing the overall efficiency of operations. In Bong and Kap (2011) the authors investigate the problem of scheduling container transfer operations in rail terminals and suggest a mathematical model to minimize the makespan. A recent study (Gharehgozli et al. 2022) proposes a model for scheduling the operations of loading and unloading trains at a container terminal, minimizing delay times.

Research in optimizing operations in container terminals is crucial for improving efficiency, reducing costs, and minimizing environmental impacts. In this context, various approaches have been proposed to address specific challenges related to port activity planning and optimization. The research in Sumin et al. (2022) focuses on the planning problem of two automated stacking cranes in an automated environment with the goal of improving operational efficiency. Similarly, another study presented in Mei et al. (2017) proposes an integer programming model to optimize yard crane scheduling, with a focus on reducing energy consumption by optimizing the scheduling of gantry cranes. In Eilken (2019), the authors focus on the relocation problem during retrieval operations in container terminals; their aim is to optimize the planning of storage, retrieval, and relocation operations. The study proposed in Wengian et al. (2021) implements a stochastic model to obtain a fixed scheme with the minimum expected value of yard crane makespan and total task waiting time. In summary, these studies offer innovative scheduling approaches to solving specific challenges in port operations optimization. However, further research is needed to assess the effectiveness and practicality of such approaches in real and dynamic operational contexts. In the case of rehandling and reallocation of containers, Kap and Sanghyuk (2021) propose a heuristic algorithm to reduce delays, by reducing rehandles.

More recently, in addition to the need to optimize loading and unloading operations, there is also a growing interest in environmental sustainability and energy conservation. In fact, the current landscape of research in automated container terminals reflects a significant commitment to the development of innovative strategies aimed at improving operational efficiency while promoting sustainability. In specialized literature, there are numerous studies adopting various approaches geared towards optimizing operations and reducing energy consumption. A notable contribution, by Zhong et al. (2023), outlines the importance of an integrated approach, focusing on the analysis of quay cranes, automated guided vehicles, and yard cranes. This study introduces a mixed-integer programming model, accompanied by a genetic algorithm, designed to minimize energy consumption during loading and unloading operations. Similarly, research such as this mentioned in (Gao et al. 2023; Zhong et al. 2019; Xin et al. 2015) explores algorithms, aiming to maximize operational efficiency. Other studies, such as (Geerlings et al. 2018; Tan et al. 2021), concentrate on seeking innovative solutions for crane management, both onshore and ship-to-shore. The research presented in Zhong et al. (2020) is focused on managing trajectories and paths of automated guided vehicles, aiming to optimize routes and reduce delay times. Thus, the current research landscape in container terminals constitutes fertile ground for innovation, where integrated planning, energy optimization, and intelligent operations management converge to outline the future of this crucial component of maritime logistics.

3 Handling Sequencing Priority Rules

We consider the flow of import containers in a marine terminal, focusing on the storage area of these containers, intended for forwarding by rail. A variable capacity of the yard is assumed depending on the configuration under analysis (see the computational results section). The maximum height of a stack is set at 6. Furthermore, a fully occupied yard with a completely empty tier is initially considered to leave space for the reallocation of containers. A random function, available in MATLAB, was used to assign delivery times to containers. This allowed us to estimate possible delays caused by maneuvering in the yard. One of the main assumptions made about the crane used is that it can operate along a single row at a time, i.e., at a fixed position along the y-axis, thereby removing one degree of freedom from the possible movements of the crane. An illustrative image of the case of study context is shown in Fig. 1.

The goal of the research is to determine the optimal sequence of container allocations by proposing and evaluating four rules based on different priority sequences for the crane. For each rule, the following measures are calculated: energy consumption, processing times, dwell time in the yard, delays, early arrives, as well as the maximum observed delay. These measures provide a detailed overview of the performance of the crane and yard system in each of the four analyzed strategies. An optimization procedure is proposed with the aim to

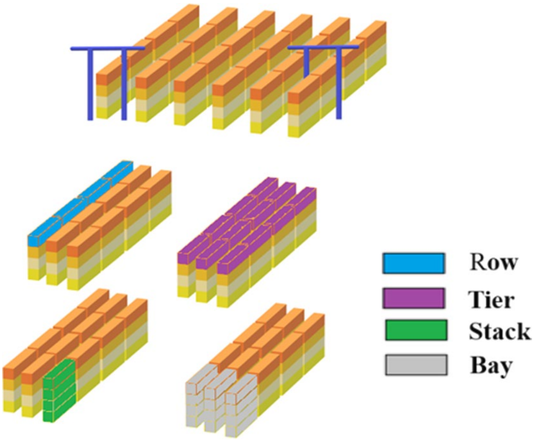


Fig. 1 Simplified yard configuration

evaluate the container positioning in the yard that locally minimizes both energy consumption and delays by varying the configuration of containers in the storage area, maintaining the initial delivery times. Delays are calculated according to the times containers are loaded onto trains compared to their planned time.

The optimization procedure determines the sequence of container unloading and reallocation during a rail loading operation. A rail mounted gantry crane is considered.

The four proposed sequencing rules are defined as follows.

- *Rule 1*: the crane unloads the containers in priority order based on their delivery times, regardless of the tier they are in. If the container to be unloaded has other containers positioned above it, the crane will reallocate them either to a row where all priorities are subsequent, or to an empty row or the nearest free space, following this hierarchy of choice.
- *Rule 2*: this case applies the same strategy as rule 1 but includes a check on container reallocations. For this case we implement the function "*Climbing Control",* described in Sect. 4. This function permits a tier-off difference of no more than two to allow constant visibility for the crane operator.
- *Rule 3*: the crane unloads the container in priority order based on their delivery times, emptying one tier at a time. In this rule, reallocations are not necessary, since containers below the level to be emptied are not considered until the upper level has been completely emptied.
- *Rule 4*: the crane unloads the container in priority order, regardless of the tier it is in. If the container to be unloaded has other containers positioned above it, the crane will reallocate them either to a row where all priorities are subsequent, or to an empty row or the nearest open space, choosing the closest position among these. As in rule 2, the "*Climbing Control"* function is also used in this rule.

For the calculation of the handling times, movements are divided into the following four categories, although weight-dependent consumption is not considered in this research:

- M1: when the empty crane works moving along a row, it uses trolley traveling speed.
- M2: when the empty crane works moving vertically, it uses hoisting no-load speed.
- M3: when the loaded crane works moving along a row, it uses trolley traveling speed.
- M4: when the loaded crane works moving vertically, it uses hoisting load speed.

The four chosen rules aim to replicate practices at the terminal. Currently, the choice of how to handle containers is left to the crane operator, who faces both visual and delivery constraints. Rule 1 does not consider the visual constraints of the crane operator, while the hierarchical selection of where to relocate the containers aims to minimize empty movements. Similarly, rule 2 reduces empty movements by simulating the crane operator's visual constraints. Note that rule 4 reallocates containers to the nearest spaces, simulating the crane operator's visual constraint, without necessarily reducing empty movements but reducing the crane's working times. Rule 3, unloading containers one tier at a time, is a technique commonly used but does not consider priority constraints. In this study, to introduce a priority constraint in rule 3, the unloading order of the containers along each tier is chosen by unloading them according to their delivery priority.

4 Proposed optimization procedure

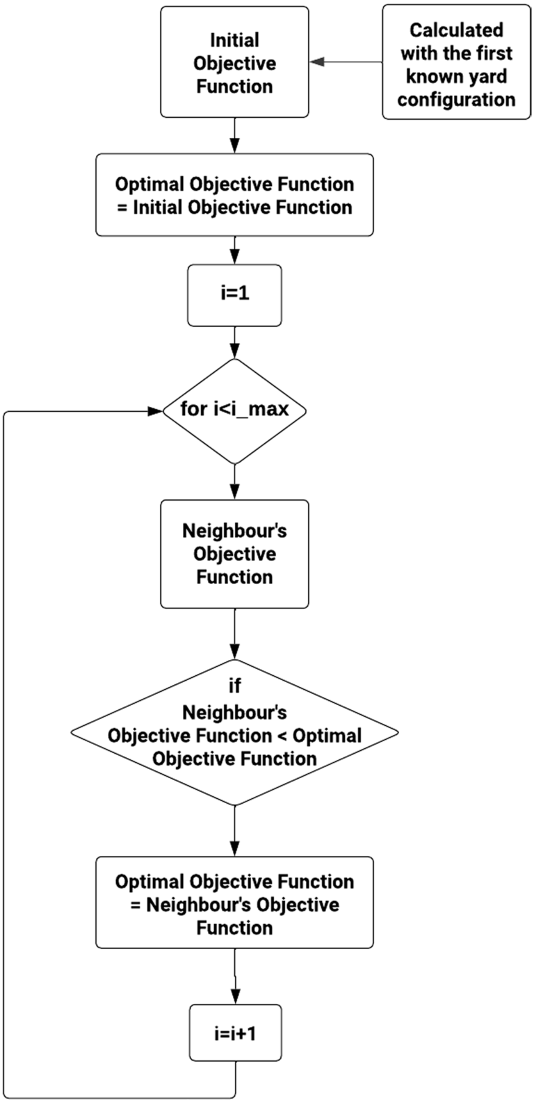
In the optimization phase, an ad hoc hill climbing algorithm has been developed. The same approach in the context of marine terminal efficiency is used also in Yurtseven et al. (2018), where the authors confront the vessel stowage problem.

Hill climbing is a local search iterative optimization method. Figure 2 reports a flowchart representing the main steps of the algorithm.

The first step is related to the definition of the initial best solution. In our procedure, for each rule the initial optimal value is set as the value of the objective function calculated with the initial yard configuration. Then, a neighbor solution is selected and compared with the initial optimum. If the new value is better than the previous one, it is replaced by the best new solution. For the selection of neighbors, a stochastic random choice is used. More precisely, the neighbor is found starting from the previous configuration by changing the position of two containers maintaining their own due time. As stopping criterion, the maximum number of iterations is fixed.

It is important to emphasize that the proposed method aims to avoid unnecessary handling operations in advance. In fact, by possessing information about the containers to be forwarded by rail, it is possible to decide where to place them in the yard while waiting for their loading on train.

Fig. 2 Hill climbing algorithm



To validate the solution obtained by the hill climbing algorithm, the optimal solution obtained by applying the "Last Tier First Row Unloading" (LTFRU) rule is considered, as referring value for evaluation of the best solution. This lower bound solution involves unloading containers one row at a time, starting from the last tier, assuming that the containers are stacked so that those due for delivery imminently are unloaded first. LTFRU minimizes container movements, as no reallocations are required, thereby minimizing crane energy consumption. Additionally, it optimizes crane movement times, positioning containers with higher priority near delivery areas. This configuration reduces processing times, especially for containers with imminent deadlines.

It is worth noting that the solution found by LTFRU does not reflect the complexity found in port terminals, where container positioning is subject to constraints such as weight or vessel arrivals. Therefore, its solution is not feasible from an operating point of view. Instead, the implemented procedures aim to accommodate the complexity and subjectivity inherent in each terminal, giving more realistic results. Consequently, the implemented rules often exhibit significant deviations from the lower bound of performance indices, as we report in the next section. Furthermore, it should be noted that the proposed control rules refer to those implemented in the reference terminal according to the management planning and equipment used. However, different rules can also be easily integrated.

Three objective functions have been studied: minimisation of overall energy consumption; minimisation of maximum delay; and a multi-objective function combining the previous two. The mathematical formulations of these objective functions and the constraints related to them are reported and explained in detail in Appendix 1.

In the implementation of the optimisation procedure, several functions are created, used in our four sequencing rules. These procedures have been implemented to replicate the complexity of decisions made by crane operators. An overview of the main functions utilized is reported below:

- *Above-tier check*: as shown in Fig. 3 this function checks if there are no containers to be reallocated above the container to be unloaded. If there are containers to be reallocated, the function counts the number and calls the functions responsible for the relocation.

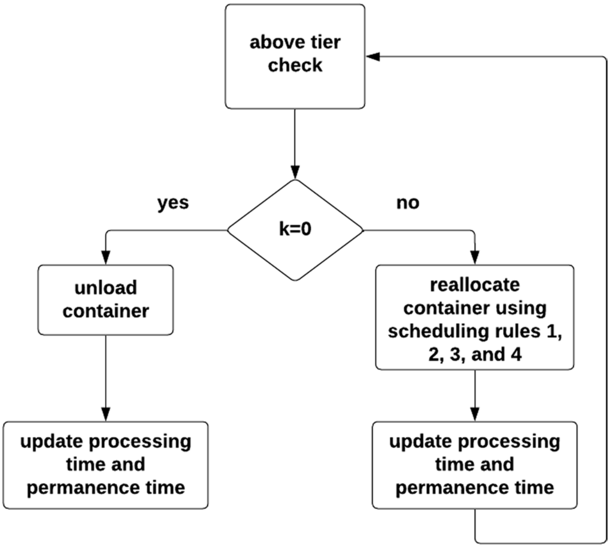


Fig. 3 Above-tier check

- *Row less priority check*: this function checks whether there are rows with container priority following the one to be reassigned.
- *Empty row check*: this function searches for any empty row where the container can be reallocated.
- *Free space*: this function searches for the nearest empty slot for reallocation.

Additionally, a function called "*Climbing Control*" has been implemented, and it is only used in rules 2 and 4. This function checks if the new position where the container is to be placed is visible to the crane operator. In particular, it checks whether there are more than two containers to be bypassed during the relocation, and whether the position to which the container is to be transferred has no more than two adjacent containers stacked on top of each other. Regarding the calculation of the processing time for each container, the data is saved in four different variables depending on the movement performed by the crane and updated each time the container is reallocated or unloaded.

5 Computational experiments

The results are obtained through the computational implementation of the procedures using MATLAB R2023b.

In all sequencing rules, the initial configuration assumes a fully occupied yard with one completely empty tier, to allow space for container reallocations as specified in constraints (7) and (8) in Appendix 1. Regarding the number of rows, the analysis is performed for values ranging from 6 to 25—$N_x = (6, 10, 15, 20, 25)$—thus observing the procedure's response to an increasing number of containers processed. Data on speed, energy consumption and crane size were derived from Henan Tosta Machinery Co. and are reported in Table 1. $v_{\text{yun,}}$ $v_{\text{zun,}}$ $v_{\text{yload,}}$ v_{zload} indicate speeds values during unloading/loading movement along y and z axis. H is the operational height of the crane and e represents crane's energy consumption. The TEU is considered as the measure of container dimensions.

The initialization of yard with the due times is done via a controlled random generation, using the '*randi*' Matlab function. $D_{\text{time min}}$ is fixed to 10 min, a value chosen to guarantee initialization process, $D_{\text{time max}}$ is calculated considering a medium handling time of 2 min for each container managed.

The data presented in the following tables and graphs stem from two types of analyses. The first analysis concerns the first two objective functions, where we

Table 1 RMG crane specifications

$v_{\text{yunloaded}}$	75m/min
v_{yloaded}	75m/min
$v_{\text{zunloaded}}$	36m/min
v_{zloaded}	18m/min
e	300kWh
H	18m

varied the number of rows for both functions and run 100 instances for each case. In the second analysis, we examined the multi-objective objective function by varying the weight parameters alpha and beta, with $a=(0, 0.2, 0.4, 0.6, 0.8, 1)$, while keeping the number of rows constant at 10. In the last case, we examined 50 instances for each case. For both phases the instances are generated by random assignment of due time controlled by a seed.

We present the computed gap according to the following formula:

$$\text{gap} = \frac{z - z_{\text{LTFRU}}}{z}\% \tag{1}$$

As explained in the previous paragraph, the chosen initial value is very tight resulting in very high gaps.

Furthermore, relative improvements between the initial solution and the local minimum obtained from the algorithm are reported below, calculated by:

$$\Delta = \frac{z_{\text{initial}} - z_{\text{optimal}}}{z_{\text{initial}}}\% \tag{2}$$

The stopping criterion, determined from initial tests, sets the maximum number of iterations to 1000. It is observed that the iteration where the optimal configuration is found occurs around the six-hundredth iteration.

The following graphs and tables report the results obtained during the data collection phase conducted with 100 instances for each case. In Figs. 4 and 5, we present the outcomes of the minimisation of overall energy consumption objective function (cf. (3) in Appendix 1), illustrating variations based on the applied rules (Fig. 4) and the number of containers handled (Fig. 5). The graphs do not include the optimality gap for rule 3, having an identical energy consumption as the referenced value.

In Table 2 we tabulate the average values of the gap calculated as (1) obtained during the analysis, while in Table 3 we give the average values of the improvement calculated as (2). From these tables, it is evident that there is a degradation in procedure performance with an increase in the number of handled containers in all rules.

Table 3 highlights significant improvements in scenarios utilizing rules 2 and 4, with peaks of objective function improvements of up to 43%. It is also relevant to note that the minimum gaps correspond to the maximum improvements, denoting a good behavior of the procedure. According to our findings, rule 3 emerges as the best choice for reducing the gap (Table 2) but not for improving the performance of the container terminal (Table 3), in fact the energy consumption calculated with rule 3 is always the same.

The graph in Fig. 6 shows the results of rules 2 and 4 for the same objective function. The graph reports the initial consumption values and those following the application of the optimization algorithm. It highlights the maximum improvement values of rule 2 (43%) and rule 4 (38%) in term of KW used for all the unloading procedure.

For the first objective function, which aims to minimize energy consumption, we evaluated the resulting monetary savings. To make this assessment, the electricity prices reported in (ARERA 2022) were considered. The terminal under

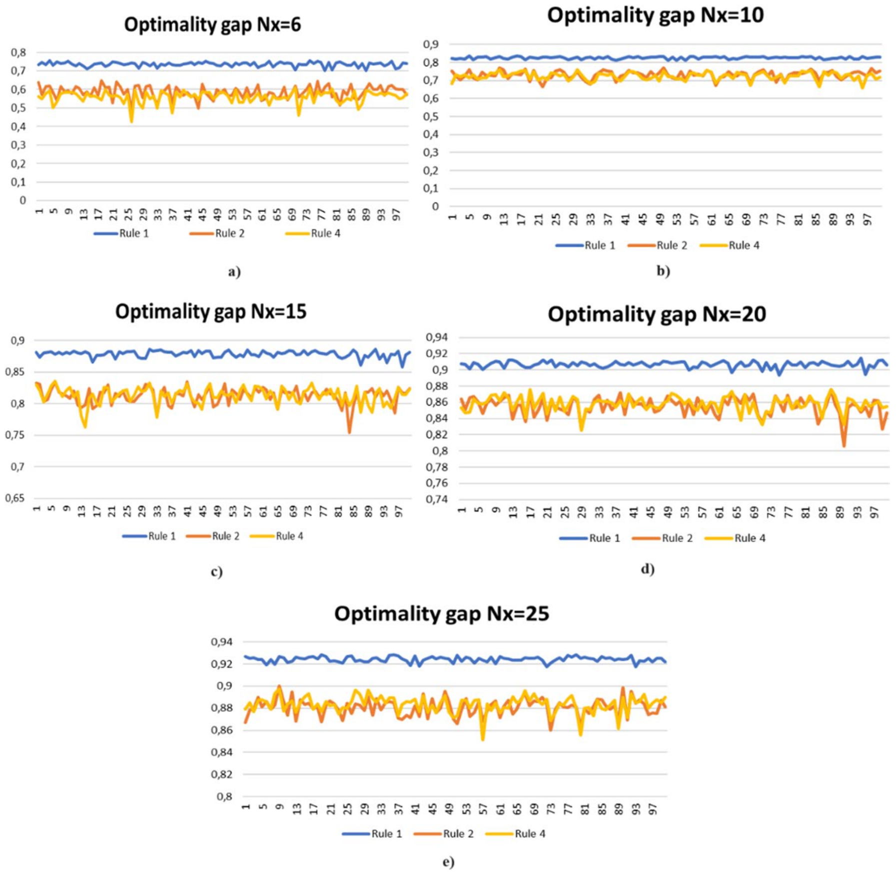


Fig. 4 Results of (1) for the first objective function stored by managed container: **a** 24 containers; **b** 40 containers; **c** 60 containers; **d** 80 containers; **e** 100 containers

analysis, as described in (PSA Italy 2024), has an average electricity consumption of about 25.567 MWh and, according to the EU average price, is subject to an average gross tariff of 0.1308 €/kWh. Thanks to the data collected from the two reports mentioned above, it was possible to evaluate the weekly savings obtained in monetary terms, resulting from the application of the optimisation procedures proposed in this study. Assuming the number of trains departing from the terminal to be 60 (Port of Genoa 2024), the results shown in Table 4 were obtained. It should be noted that these savings were obtained only by reorganizing the yard in advance according to the proposed sequencing rules, without considering any additional equipment resources.

Similarly to the results of minimisation of overall energy consumption, Figs. 7 and 8 illustrate the results related to the minimization of the maximum tardiness (see (4) in Appendix 1), highlighting variations in response to the applied sequencing rule (Fig. 7) and the number of containers handled (Fig. 8).

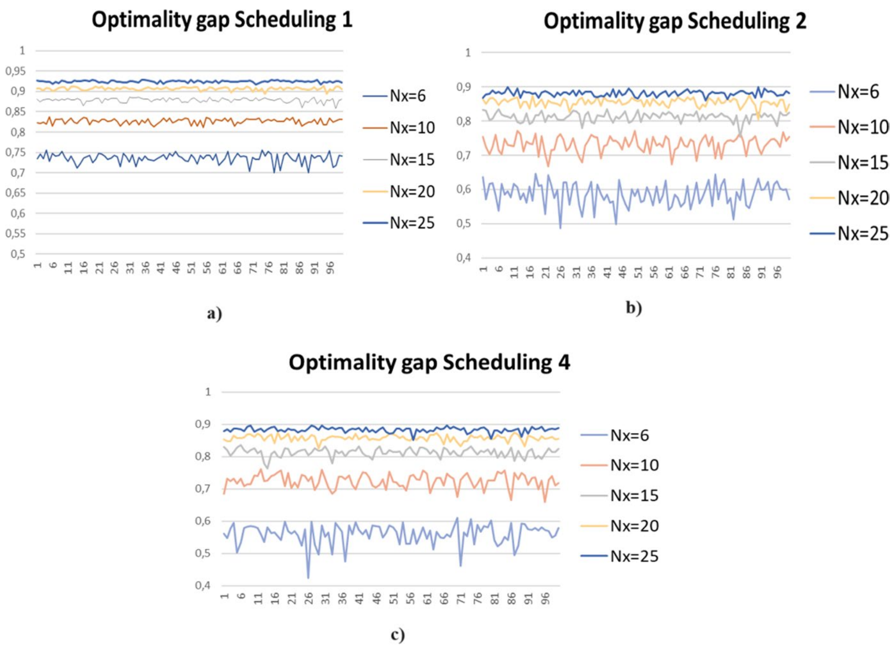


Fig. 5 Results of (2) for the first objective function stored by scheduling rule: **a** rule 1; **b** rule 2; **c** rule 4

Table 2 Medium value of gap (1) for the first objective function

N_x	Number of containers managed	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
6	24	74	59	0	56
10	40	83	73	0	72
15	60	88	81	0	81
20	80	91	86	0	86
25	100	92	88	0	88

Table 3 Medium value of improvement (2) for the first objective function

N_x	Number of containers managed	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
6	24	24	43	0	38
10	40	22	38	0	34
15	60	22	35	0	31
20	80	19	32	0	29
25	100	18	30	0	29

Fig. 6 Initial and optimized value of the most relevant results of the first objective function with the improvement value tabulated

Table 4 Medium value of weekly monetary savings [€]

N_x	Number of containers managed	Rule 1 [€]	Rule 2 [€]	Rule 4 [€]
6	24	47	70	54
10	40	129	177	146
15	60	322	397	341
20	80	566	72	637
25	100	916	114	1095

Tables 5 and 6 report, respectively, the medium values of the gap and the improvement calculated as (1) and (2). The results used for the average were stored during the data collection phase, involving also 100 instances in each case. Data analysis in Tables 5 and 6 reveals that rules 3 and 4 are closer to the established lower bound. Unlike what happened for the first objective function, in this case the minimum gap does not correspond to the maximum improvement. Lower gaps are obtained with a high number of managed containers, while greater improvements are obtained with few managed containers. Using this objective function, even the yard management strategy as described by rule 3 can be minimized. For the other three rules, the improvements are instead lower compared to first objective function, but better gaps can be observed, approaching closer to the lower bound.

Figure 9 highlights how it is possible to improve maximum delay by up to 55% using rule 3 in the port management system. The graph reports the value of this objective function in minutes, given a realistic representation. This result allows for decisions on optimizing rule 3, which previously showed no improvements in crane energy consumption.

The following graphs and tables report the results obtained during the data collection phase conducted with 50 instances for each case. For the last objective function, that is the multi-objective function combining the previous ones (see (5) in Appendix 1), a different investigation was conducted, analyzing the procedure with a fixed number of 60 handled containers, changing α value.

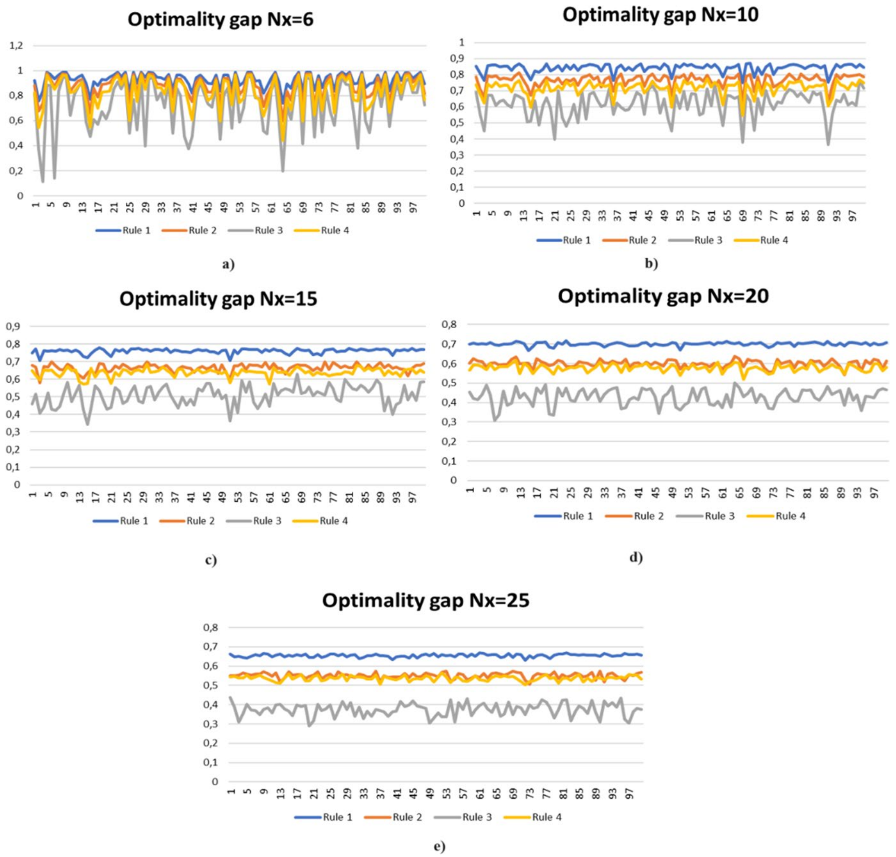
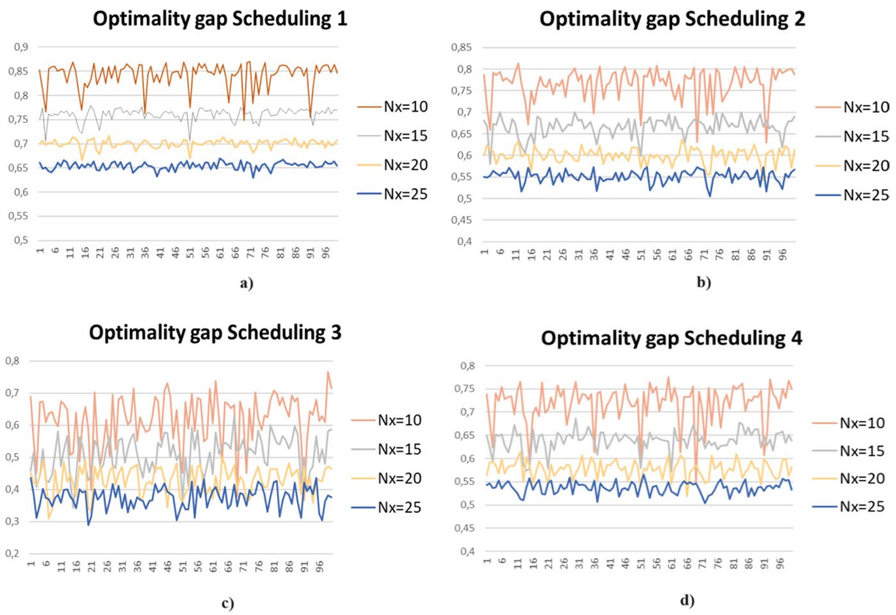


Fig. 7 Results of (1) for the second objective function stored by managed container: **a** 24 containers; **b** 40 containers; **c** 60 containers; **d** 80 containers **e** 100 containers

The results, depicted in Figs. 10 and 11, are divided based on the α coefficient assigned to the multi-objective function (Fig. 10) and according to the applied rules (Fig. 11).

In reference to the results presented in Tables 7 and 8, we can observe how the procedure responds better at lower alpha values—cases where greater emphasis is placed on the makespan. From Table 8 it is evident that the choice of rule 4 has the greatest improvements compared to the initial configuration, but scheduling rule 3 maintains lowest gap compared to the others. Comparing gap and improvement (Tables 7 and 8), rule 4 results as the best one.

Finally, Fig. 12 highlights the most significant results of the multi-objective function, obtained through rules 3 and 4. It is observed that, despite rule 3 maintaining the lowest gaps (as reported in Table 7), it shows inferior improvements compared to rule 4.



a)

b)

c)

d)

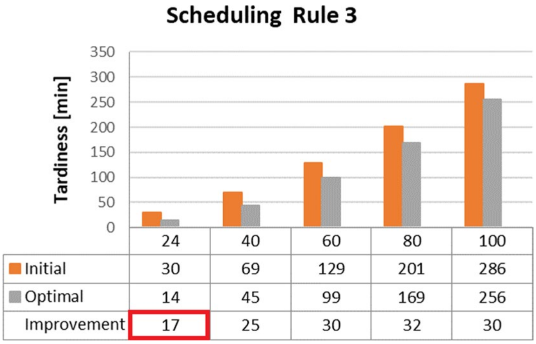
Fig. 8 Results of (2) for the second objective function stored by scheduling rule: **a** rule 1; **b** rule 2; **c** rule 3; **d** rule 4

Table 5 Medium value of gap (1) for the second objective function

N_x	Number of containers managed	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
6	24	93	88	73	83
10	40	84	77	62	72
15	60	76	67	51	64
20	80	70	60	43	58
25	100	65	55	37	54

Table 6 Medium value of improvement (2) for the second objective function

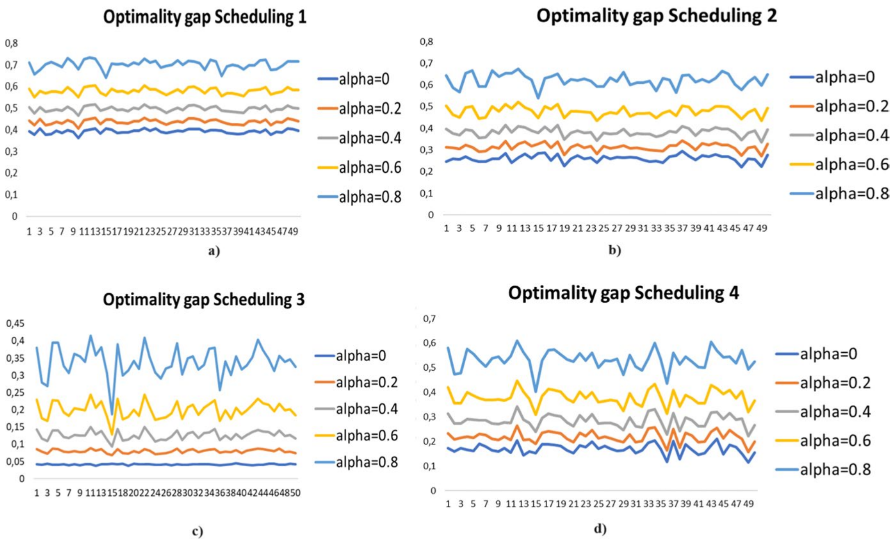
N_x	Number of containers managed	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
6	24	23	44	55	44
10	40	19	31	36	31
15	60	15	24	23	22
20	80	12	20	16	19
25	100	11	17	11	16



	24	40	60	80	100
🟧 Initial	30	69	129	201	286
⬜ Optimal	14	45	99	169	256
Improvement	17	25	30	32	30

Fig. 9 Initial and optimized value of the most relevant results of the second objective function with the improvement value tabulated

Fig. 10 Results of (1) for the combined objective function stored by α value: **a** $\alpha = 0,$ **b** $\alpha = 0, 2$ **c** $\alpha = 0, 4$ d) $\alpha = 0, 6,$ **e** $\alpha = 0, 8,$ **f** $\alpha = 1$



a) b) c) d)

Fig. 11 Results of (2) for the combined objective function stored by scheduling rule: **a** rule 1, **b** rule 2, **c** rule 3, **d** rule 4

Table 7 Medium value of gap (1) for the combined objective function

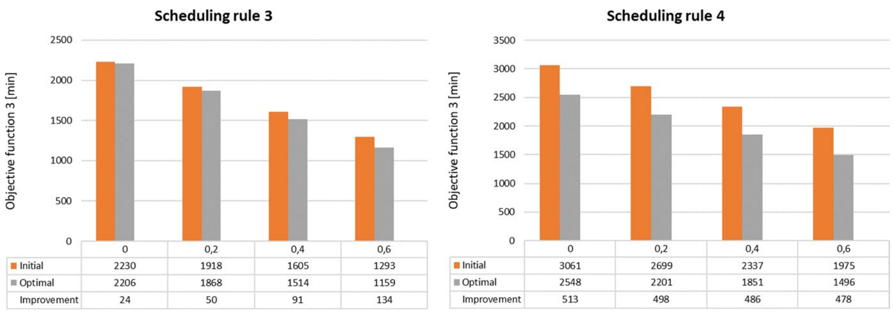
Alpha	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
0	39	26	4	17
0,2	44	31	8	22
0,4	50	38	13	28
0,6	58	48	20	38
0,8	70	62	34	53
1	90	87	71	83

Table 8 Medium value of improvement (2) for the combined objective function

Alpha	Rule 1 (%)	Rule 2 (%)	Rule 3 (%)	Rule 4 (%)
0	12	17	1	17
0,2	13	18	3	18
0,4	15	19	6	21
0,6	17	21	10	24
0,8	20	25	18	29
1	25	30	33	38

6 Conclusions

We propose and evaluate different rules to determine the best sequence in which import containers in a marine terminal should be taken from the yard and loaded



Scheduling rule 3

	0	0,2	0,4	0,6
■ Initial	2230	1918	1605	1293
■ Optimal	2206	1868	1514	1159
Improvement	24	50	91	134

Scheduling rule 4

	0	0,2	0,4	0,6
■ Initial	3061	2699	2337	1975
■ Optimal	2548	2201	1851	1496
Improvement	513	498	486	478

Fig. 12 Initial and optimized value of the most relevant results of the combined objective function with the improvement value tabulated

onto trains for inland forwarding. The objective of the study is twofold: minimizing the energy consumption of the cranes loading the trains, and minimizing the maximum delay with which containers are loaded with respect to their planned delivery time. The proposed sequencing rules were implemented based on the operational procedures in force at the reference terminal of Genoa. Nonetheless, they are fully flexible to be adaptable and integrable to the particular circumstances of terminals in general. In addition, different types of equipment used for container handling could be considered, as well as other data on energy consumption or crane handling times. These rules are then included in an optimisation procedure precisely to determine the best performance indices with respect to the set objectives. As far as energy consumption is concerned, the best sequencing rule, where the crane unloads containers first in priority order according to their delivery time, minimizing reallocation, results in a Kw saving of about 43% compared to the initial yard configuration. It is worth noting that this percentage value corresponds to a very significant monetary saving of over €1000 for a single RMG crane. Finally, it should be noted that this result can be achieved with a simple reorganization of container positioning in the yard, without the need for additional resources.

It should be emphasized that an innovative aspect of our sequencing rules, and the optimisation procedures, proposed to organize the yard a priori, to make train loading more effective, are very simple to implement and easily adaptable to any operational reality. Therefore, in light of the ongoing digitalisation process to maximize the efficiency of container terminals, these procedures are certainly to be recommended to any port authority. Moreover, based on the results reported in Appendix 1, the authors suggest that the management of marine terminals should apply the proposed optimisation procedures to make the port more efficient, more profitable, busier and thus more competitive without requiring additional resources. A natural extension of this work could involve a greater number of management constraints for the yard, an increase in the degrees of freedom of the cranes, and an implementation of different types of containers handled, such as reefer and dangerous goods.

Appendix 1. Mathematical model and notation

The decision variables of the problem are defined here, together with the mathematical formulation of the three considered objective functions and constraints. The required notation is introduced first.

$N_x\, N_z$	Number of rows and number of tiers.
$i \in N_x\, j \in N_z$	Index for row and index for tier.
$T_{ij}^{\text{xun}}\, T_{ij}^{\text{zun}}\, T_{ij}^{\text{xload}}\, T_{ij}^{\text{zload}}$	Container's time value of unloading/loading phase along z and x
C_{ij}	Crane's consumption for each container
D_{timeij}	Container's due time
$Y_{\text{time}ij}$	Container's permanence into yard time
$P_{\text{time}ij}$	Container's processing time
$i_{\text{real}}\, j_{\text{real}}$	Reallocation position
P_{i*j*}	Priority of container to unload

The priority P_{ij} associated with a movement of a container into a position (i,j) is defined as follows: $P_{ij} = \begin{cases} 1 & \text{for } D_{\text{time min}} \\ N_x\left(N_z - 1\right) & \text{for } D_{\text{time max}} \\ 0 & \text{for empty space in the yard} \end{cases}$

According to the above notation, the considered performance indices can be then expressed as:

$$\text{makespan} = \max\left(Y_{\text{time}ij}\right);$$

$$\text{lateness}_{ij} = Y_{\text{time}ij} - D_{\text{time}ij};$$

$$\text{tardiness}_{ij} = \max\{0, \text{lateness}_{ij}\};$$

$$L_{\max} = \max\{\text{lateness}_{ij}\};$$

$$T_{\max} = \max\{\text{tardness}_{ij}\}.$$

In the above notation, i and j are the indices indicating the row and tier position, respectively, of each container. Moreover, i^* and j^* indicate, respectively, the row and tier position of the container to unload, while i_{real} and j_{real} give its new row and tier reallocated position.

The following five binary variables have been introduced to control the handling processes and aid in decision-making during the container movements. The variables refer to the portion in the yard served by the crane.

$$k_1 \in \{0,1\}\begin{cases} 0 & \text{if the above tier is empty} \\ 1 & \text{otherwise} \end{cases}$$

$$k_2 \in \{0,1\}\begin{cases} 0 & \text{if there is at least one tier with} P_{ij} > P_{\text{container to move}} \\ 1 & \text{otherwise} \end{cases}$$

$$k_3 \in \{0,1\}\begin{cases} 0 & \text{if at least one tier is empty} \\ 1 & \text{otherwise} \end{cases}$$

$$k_4 \in \{0,1\}\begin{cases} 0 & \text{if there is at least one free space} \\ 1 & \text{otherwise} \end{cases}$$

$$k_5 \in \{0,1\}\begin{cases} 0 & \text{there are no obstacles exceeding two containers} \\ 1 & \text{otherwise} \end{cases}$$

Readers can easily note that each of the above variables avoids the corresponding movement if it is set to one. It is worth noting that in the present paper the proposed control rules are those implemented in the referring Genoa terminal according to the management planning and the equipment used. Of course, different rules can be integrated as well.

The present research considers the value of different objective functions to evaluate the impact of the scheduling rules on the overall system performance. These objective functions are given in Eqs. (3)–(5):

$$\min z_1 = \sum_{i=1}^{N_x} \sum_{j=1}^{N_z} C_{ij} \tag{3}$$

$$\min z_2 = T_{\max} \tag{4}$$

$$\min z_3 = \alpha \sum_{i=1}^{N_x} \sum_{j=1}^{N_z} \text{tardiness}_{ij} + \beta \text{makespan} \tag{5}$$

As already said, objective function (3) represents the minimization of the overall energy consumption, while (4) minimizes the maximum tardiness. The multi-objective function (5) is a linear combination of two quantities, expressed in minutes, and aims to minimize both a representative delay value and the energy consumption. Values α and β in (3) are such that $\alpha + \beta = 1$. The first term represents the sum of the delays accumulated by all containers, while the second one indicates the processing time, representing the crane's operational time.

Once the objective functions are established, the following procedural constraints are taken in consideration:

$$D_{\text{time min}} \leq D_{\text{time } ij} \leq D_{\text{time max}} \tag{6}$$

$$D_{\text{time } i1} = 0 \tag{7}$$

$$\sum_{i=1}^{N_x} \sum_{j=1}^{N_z} P_{ij} = 0 \tag{8}$$

$$P_{i^*j^*} < P_{ij} \quad \text{with } i \neq i^* \text{and } j \neq j^* \tag{9}$$

$$\sum_{j=j^*+1}^{N_z} P_{i^*j} = 0 \tag{10}$$

$$P_{i^*j^*} < P_{ij^*} \quad \text{with } i \neq i^* \tag{11}$$

$$\sum_{i=1}^{N_x} P_{ij} = 0 \tag{12}$$

$$k_2 + k_5 = 0 \tag{13}$$

$$k_3 + k_5 = 0 \tag{14}$$

$$k_4 + k_5 = 0 \tag{15}$$

Constraints (6) and (7) are assumptions done to create the due time values. In our study a fully occupied yard is considered, with all containers in place. Thanks to this initial assumption, constraint (6) is used to control the assignment of container due time value. $D_{\text{time min}}$ is assumed to be independent of the number of containers in the yard, while $D_{\text{time max}}$ is considered to be a function of the number of containers handled and the average value of the handling time. Constraint (7) creates the first tier completely empty allowing reallocations and maneuvering space for the crane.

Constraint (8) verifies that the yard is completely empty, thus ensuring all containers are unloaded. Constraints (9) and (10) are related to the scheduling rules 1, 2 and 4. Specifically, (9) ensures that the container to unload is the one with the highest priority, while (10) allows us to check (before unloading the selected container) that there are no other containers above it.

Constraints (11) and (12) are related to the scheduling rule 3. More precisely, constraint (11) ensures that the container to unload is the one with the highest priority on the tier taken into consideration, while (12) allows us to check that the tier is completely unloaded before unloading the next tier.

Constraints (13), (14) and (15) are relative to scheduling rules 2 and 4. These constraints control the new reallocated position of containers. More precisely,

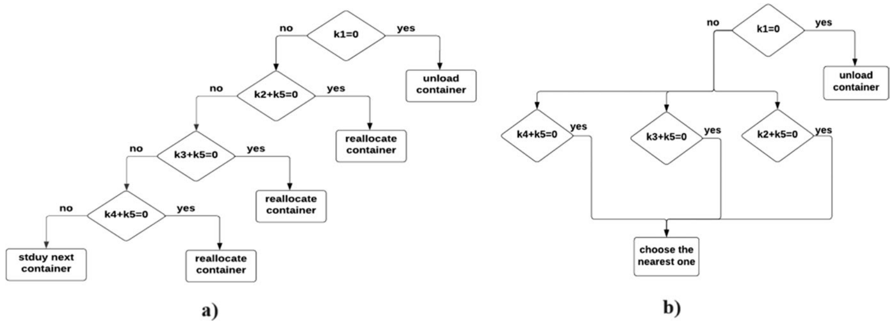


Fig. 13 **a** Constraints applied to rule 2; **b** Constraints applied to rule 4

decision variables k_2, k_3 and k_4 search for the reallocated position and k_5 controls if the "*Climbing Control*" is passed. More precisely, if all k_2, k_3 and k_4 equal 0, there is an available reallocation position where the container can be placed. Note that in the case of scheduling rule 2, being it a hierarchical choice, once constraint (13) is satisfied, the subsequent ones are not required. Instead, in scheduling rule 4, the position that satisfies one of constraints (13), (14) and (15) and is closest to the initial position is selected, aiming to reduce relocation times. An explicative flow chart about the application of constraints (13), (14) and (15) is shown in Fig. 13.

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Declarations

Conflict of interest All authors have no conflicts of interest.

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