ARCHIVES OF TRANSPORT *ISSN (print):* *0866-9546*
Volume 73, Issue 1, 2025 ***e-ISSN (online):*** *2300-8830*
DOI: *10.61089/aot2025.4f22k916*

THE IMPACT OF CONTAINER YARD LAYOUT ON THE CARGO HANDLING TIME OF EXTERNAL TRANSPORT VEHICLES IN AN INTERMODAL TERMINAL

Roland JACHIMOWSKI[1], Michał KŁODAWSKI[2]
[1,2] Faculty of Transport, Warsaw University of Technology, Warsaw, Poland

Abstract:

This article investigates the impact of container yard layout on the cargo handling time of intermodal trains operating at container terminals, with a particular emphasis on the number of stacking layers used in container storage. The study focuses on how varying vertical storage configurations influence the duration of crane loading cycles as well as the energy consumption of transshipment equipment. In addition to the stacking layout, the analysis incorporates several operational constraints that are critical in intermodal rail transport, including the locking pin arrangements on railcars, container gross weights, and axle load limitations specific to intermodal wagons. The theoretical section outlines the fundamental role of intermodal terminals within global logistics and supply chains. It delves into the organization of container storage within terminal yards, highlighting its influence on handling performance and the overall turnaround time of intermodal transport units. Furthermore, the article includes a comprehensive literature review that examines state-of-the-art research on container yard storage strategies, allocation rules, and various optimization approaches aimed at improving yard efficiency. To evaluate the operational impact of different stacking strategies, a simulation model was developed using the FlexSim platform. The model allows for detailed analysis of crane cycle times in relation to stacking configurations, while also accounting for the energy usage of cranes and handling equipment. The simulations were carried out for a range of stacking scenarios to reflect real-world variability and constraints encountered in container terminals. The findings reveal that the relationship between the number of stacking layers and train loading time or energy consumption is non-linear and often counterintuitive. Increasing the number of layers does not necessarily lead to proportional gains or losses in efficiency. Instead, certain configurations may result in operational bottlenecks or increased energy use due to additional crane repositioning and container relocations. The research not only provides quantitative evidence on the operational consequences of yard design decisions but also offers practical insights for terminal planners and operators. These insights can support both short-term operational planning and long-term strategic investments aimed at optimizing terminal performance and sustainability.

Keywords: *intermodal transport, container terminal, yard layout, stacking strategy, crane cycle time, energy consumption*

To cite this article:

Jachimowski, R., Kłodawski, M., (2025). The impact of container yard layout on the cargo handling time of external transport vehicles in an intermodal terminal. Archives of Transport, 73(1), 179-193. https://doi.org/10.61089/aot2025.4f22k916

Contact:
1) roland.jachimowski@pw.edu.pl [https://orcid.org/0000-0001-5921-2436] – corresponding author; 2) michal.klodawski@pw.edu.pl [https://orcid.org/0000-0002-4256-2189]

1. Introduction

In today's global economy, there is a growing emphasis not only on minimizing transport costs but also on reducing the environmental impact of transportation. For both reasons, intermodal transport has become an increasingly popular mode of freight movement, particularly in international logistics, as it leverages the combined strengths of maritime, rail, and road transport.

A key component of the intermodal transport system, enabling the effective use of each transport mode's advantages is the intermodal terminal. Its role goes beyond simple transshipment; it also involves activities related to storage, consolidation, and coordination of container flows in both space and time (Krześniak et al., 2022).

One of the most important aspects of intermodal terminal operations is their contribution to reducing environmental pollution caused by the transport sector. According to the priorities of the European Union's climate policy as outlined, among others, in the White Paper on Transport, reducing harmful transport-related emissions requires shifting a significant portion of freight traffic from road to other, more sustainable modes, particularly rail transport. Given the key advantages of rail transport such as its efficiency in transporting large volumes of cargo over long distances, this EU objective appears achievable, especially for selected cargo types and on specific, mostly international, routes (Europejska, 2011).

Another reason behind the growing interest in intermodal transport is the use of containers, which, as standardized units, ensure a high level of safety for transported goods and greatly facilitate the mechanization of handling processes. In addition to container handling, intermodal terminals also allow for temporary storage. The ability to store containers at terminals is significant from both operational and strategic perspectives: it allows synchronization of incoming and outgoing transport, provides a buffer in case of disruptions, and enables load optimization based on customer demand. Moreover, intermodal terminals, particularly inland ones, function as empty container depots, allowing clients to quickly access intermodal transport services (Gnap et al., 2021).

The container storage process in the yard involves not only physical placement but also strategic positioning in anticipation of planned retrieval. This complexity arises from container stacking, which restricts direct access to containers buried under others. Factors such as the height of container stacks, proximity to other units, and availability of handling equipment all determine the number of operations required for subsequent retrieval and loading onto transport vehicles. Better organization of the storage yard can significantly reduce subsequent handling cycle times performed by loading equipment.

Handling equipment is an integral component of these processes. In intermodal terminals, especially inland terminals, the most common equipment includes Rail Mounted Gantry (RMG) cranes, Rubber Tired Gantry (RTG) cranes, and reach stackers. Although essential for operational efficiency, this equipment is also a significant source of energy consumption and pollution. Their operations require considerable energy, particularly during frequent container lifting and lowering maneuvers, which are common when stacking containers high. Research shows that container lifting operations are particularly energy-intensive, with energy consumption increasing proportionally to container mass (Papaioannou et al., 2017).

Therefore, effective container storage management, reducing unnecessary repositioning, and shortening equipment operational cycles are not only logistical efficiency issues but integral to reducing energy consumption by handling equipment. Furthermore, electrifying equipment and employing hybrid drives supported by renewable energy sources can significantly decrease the emissions of intermodal terminals (Brzeziński & Pyza, 2021).

In light of these considerations, an intermodal terminal should be viewed not merely as a container handling point but as an active participant in constructing energy-efficient supply chains. In an era of energy transition and increasing pressure to optimize costs, the role of intermodal terminals is expected to grow in importance(Zabielska et al., 2023), (Izdebski et al., 2019).

This article discusses the impact of the number of container storage layers in the yard on the loading time of intermodal trains. The first chapter addresses the influence of yard layout and container organization on the transit time of intermodal units through the terminal. It also briefly describes train loading issues and associated energy consumption by handling equipment.

The second chapter provides a literature review concerning container storage yard issues. The third chapter presents a simulation model of intermodal train loading as a function of container arrangement in the storage yard and the number of stacked layers. The fourth chapter discusses the results obtained from simulation studies.

2. Organization of container storage and loading in an intermodal terminal

2.1. Containers storage problem

In addition to loading tracks and maneuvering roadways, where containers are transferred between road and rail transport, a vital element of terminal infrastructure is the storage yard, which is a designated area for temporary container storage between transfers from one transportation mode to another.

The organization and method of container storage significantly influence the overall efficiency of terminal operations, particularly affecting loading and unloading times. One key factor determining the effectiveness of these operations is the number of container stacking layers understood as the height of vertical container stacks on the yard (Ambrosino et al., 2021).

Stacking height ultimately dictates the number of required handling devices, making it especially crucial during the design phase of an intermodal terminal. Determining the appropriate number of handling devices is essential for planning their placement in various operational zones along the storage blocks, particularly concerning crane arrangements. This consideration is critical for designing the electrical infrastructure that powers handling equipment (mainly cranes) and determining the required electrical capacity for the terminal. Cranes typically represent the largest electrical load within the terminal. Although terminals can utilize equipment powered by internal combustion engines, operationally and practically, this solution is inferior, especially for large storage blocks (Jachimowski et al., 2018).

In operational practice at container terminals, containers are usually stored in multiple layers depending on the available handling equipment, spatial constraints, and safety regulations. Spatial limitations naturally lead terminals to maximize container storage within minimal space. This efficiency is achievable using gantry cranes, especially rail-mounted ones (RMG cranes), which can cover operational widths up to 90 meters perpendicular to the longitudinal axis of storage blocks.

Stacking heights can range from a single layer (container placed directly on the yard surface) to five or six layers in terminals equipped with Rail Mounted Gantry (RMG) cranes or Automated Stacking Cranes (ASC). For terminals using reach stackers, stacking heights typically vary from three to five layers. Besides equipment type, stacking height is influenced by the number of rows within the storage block. Large, dense blocks are significantly more resistant to strong winds than blocks consisting of just two or three rows. Hence, for safety reasons, operators of terminals with fewer rows intentionally do not maximize stacking height.

Although increasing stacking layers allows more efficient use of available space, it introduces significant operational consequences that directly impact loading and unloading times. The higher the container stack, the greater the likelihood that the target container, destined for loading onto railcars or trailers, will be in the lower layers. In such cases, the operator must first relocate (reshuffle) upper- layer containers elsewhere in the yard to access the target container. These additional reshuffling maneuvers are recognized in literature as a primary source of operational delays in container terminals – see Fig. 1 (Van Lancker et al., 2018). Reshuffling operations also carry risks of errors due to incorrect identification of temporary relocation sites for obstructing containers.

To retrieve container No. 2, containers No. 6 and No. 10 must first be relocated. Subsequent stages require deciding where container No. 10 will be temporarily placed, based on loading plans for containers blocked by No. 10. After relocating container No. 10, another decision regarding the placement of container No. 6 must be made. Once container No. 6 is moved, direct access to container No. 2 is possible.

The time required for reshuffling operations can significantly extend the total handling time of individual containers. For example, when a container is at the bottom of a four-layer stack, three additional reshuffling maneuvers are required, each involving handling equipment and generating extra operational costs and energy consumption. More layers mean more reshuffling operations (see Fig. 2).

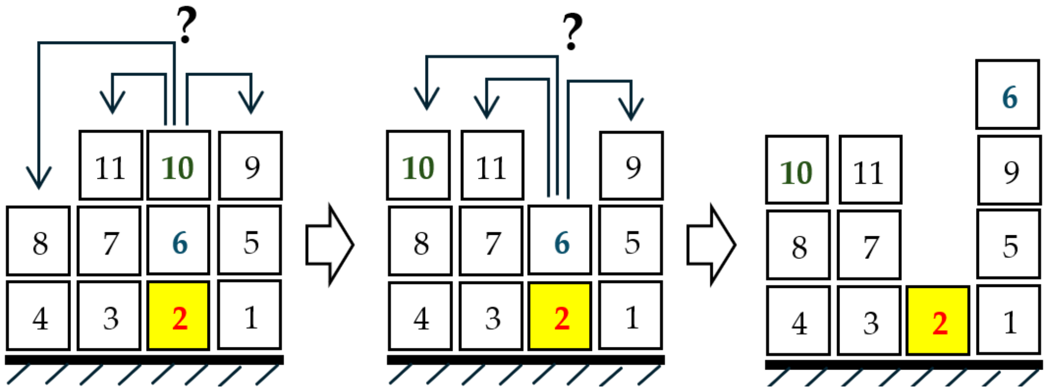

Fig. 1. Reshuffling process idea

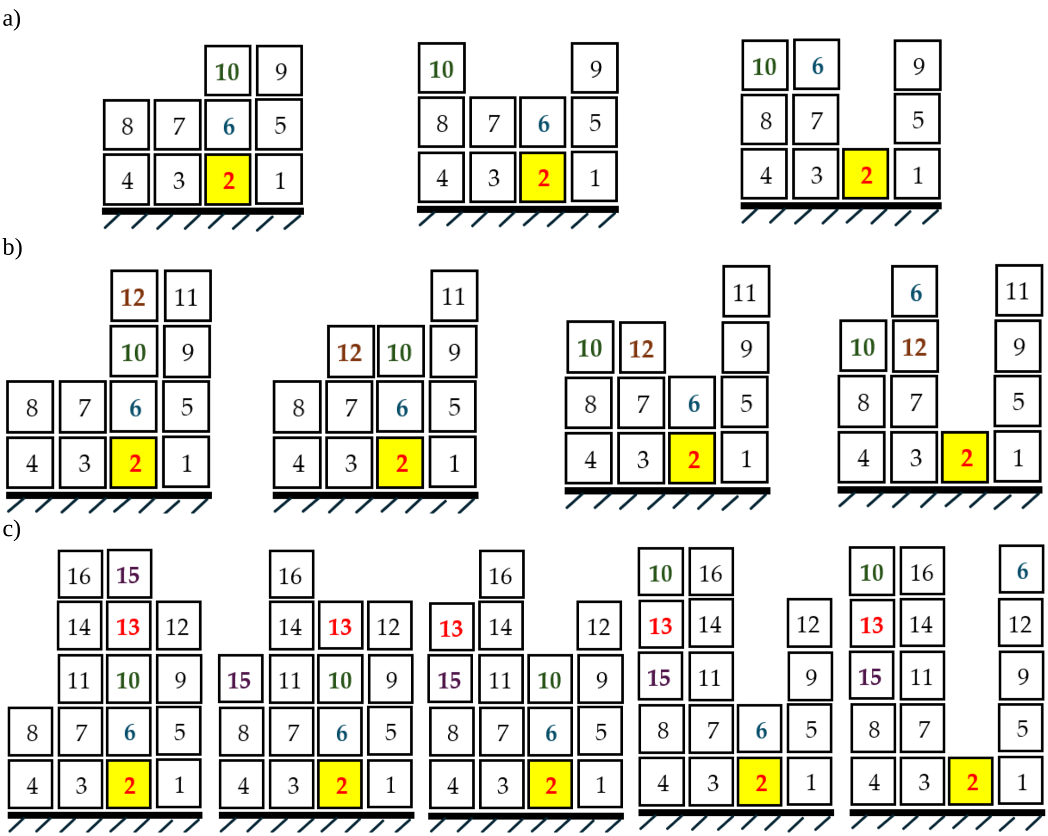

Fig. 2. Containers reshuffling depending on the number of stacking layers a) 3 layers, b) 4 layers, c) 5 layers

2.2. Intermodal train loading problem and its energy demands

In addition to container placement within the storage yard, another crucial aspect in optimizing cargo handling operations at an intermodal terminal is the process of loading the intermodal train itself. This issue is closely related to the structure of intermodal units, primarily containers, which vary in terms of dimensions and allowable gross weights. The differences in container sizes and their gross weights necessitate the use of specialized railcars and semi-trailers for their transport.

Containers are secure to transport vehicles using mounting pins. Various pin configurations allow a single railcar to carry one or more containers of different lengths. Therefore, the configuration of mounting pins on the railcars, the permissible axle loads, and the gross weights of the containers are the key factors that determine where a specific container can be placed within a given train Bruns & Knust (2012). Therefore, the issue of container storage in the yard is closely tied to the challenge of train loading. A container's position within the train is determined not only by its physical location in the yard but also by its gross weight and the configuration of mounting pins on the railcars. This topic has been discussed in detail by various authors in previous studies (Kłodawski et al., 2024a; Kłodawski et al., 2024b). The simulation models of intermodal train loading presented in those studies, developed using the FlexSim environment, enabled multi-scenario analysis of how the configuration of mounting pins on railcars and the gross weights of containers affect the loading time of outbound containers at an intermodal terminal. These constraints were also considered in the simulation model and the research presented in Chapter 3 of this article.

The arrangement of containers in the yard, along with the constraints related to intermodal train loading, directly influences loading cycle times and the associated energy consumption of handling equipment. Gantry cranes used at intermodal terminals, typically powered by electric motors, generate significant electricity demand. This energy consumption depends not only on the length of the transport cycles but also on their specific characteristics. The nature of a given cycle and the amount of energy consumed by the crane are influenced by the proportion of each motion component involved: the gantry movement along the yard, the trolley movement perpendicular to the yard axis, and the hoisting motion. As shown in studies (Kłodawski et al., 2024a), (Papaioannou et al., 2017) in seaport terminals where containers are commonly stacked in at least five layers, the highest energy consumption is associated with lifting and lowering operations. In contrast, in inland terminals where stacking heights are lower, the dominant contributor to crane energy use is the gantry movement itself. This confirms that container placement within the yard and the number of stacking layers, along with the resulting need for reshuffling, directly determine not only the duration of loading cycles but also energy consumption, which does not always correlate linearly with time.

Therefore, in addition to analyzing the impact of stacking height on intermodal train loading cycle times, this article also examines the related energy consumption. The formulas used in Chapter 3 to calculate energy demand are derived from our earlier publication (Kłodawski et al., 2024a), where they are discussed in detail.

3. Literature review on container storage in intermodal terminals

In the literature, the problem of container storage in the yard of an intermodal terminal is commonly referred to as the Container Stacking Problem (CSP). It is a broad topic that encompasses various aspects of the storage process. Most of the existing literature focuses on container storage in seaport terminals. As highlighted by literature reviews, relatively few studies have addressed this issue in the context of inland terminals, where the container yard differs from that of a seaport terminal not only in layout but also in its operational functions.

In its original form, this problem primarily relates to:

– Determining container storage locations within the terminal yard in order to maximize yard space utilization and minimize transport cycles (space allocation problems) (Chenhao et al., 2020). In such cases, storage space is typically allocated to a group of containers rather than to individual units, for example, by assigning yard areas to containers destined for the same vessel, grouping containers by ownership, designating space for transshipment operations between mainline and feeder vessels within the terminal, or for transfers between different terminals (Lee et al., 2012).

- Determining the exact location of a container within the storage yard by specifying the storage block, stack, bay, and stacking layer. This location is typically indicated to the crane operator by the Terminal Operating System (TOS). When placing the container in the assigned location, the crane operator must additionally confirm task completion within the system.
- Reshuffling containers within the yard to enable access to other containers or to facilitate their future retrieval, with the goal of minimizing the number of moves during container pickup (Caserta et al., 2012). In this case, containers may be reshuffled within the same bay to access obstructed containers or moved between different bays. The yard is typically divided into zones based on the anticipated dwell time of containers (e.g., monthly or daily stacks). Each container must be relocated to the zone corresponding to its expected remaining dwell time. Container movements may also be prioritized according to vessel departure schedules, in order to streamline future retrieval operations.

The problem of container storage can be considered from both a static and a dynamic perspective. In the static version of the problem, container placement locations in the yard are planned in advance based on known information regarding the container's arrival at the terminal.

In the dynamic approach, the decision regarding a container's location in the yard is made in real time, taking into account changing terminal conditions—such as delays in deliveries or pickups, limited availability or partial failure of handling equipment, or urgent customer requests for the retrieval of specific containers.

The process of storing containers in a container terminal yard requires the application of specific location assignment rules, which directly affect the terminal's operational efficiency, the number of container relocations, handling times, and the servicing of both inbound and outbound containers. The literature identifies three main categories of assignment rules: block assignment, bay assignment, and stack assignment (Van Asperen et al., 2011).

Block assignment rules focus on selecting the appropriate area of the storage yard for inbound or outbound containers. These rules take into account factors such as the container's purpose, type, size, and planned departure time, with the aim of streamlining handling operations and reducing potential conflicts between cranes.

Bay assignment rules determine in which bays within a given block containers should be stored. For example, the concentrated location rule involves grouping containers within specific bays in order to minimize the number of future relocations. (Woo & Kim, 2011). The nearest location rule, on the other hand, assigns containers to bays located closest to the quay (for export) or to the gate (for import).

Stack assignment rules specify the exact storage position of a container within a bay. The most commonly used strategies include: random storage, stack height balancing, segregation rule, selection of the stack with the greatest available height, nearest position relative to the gate or quay, and the priority rule, which states that containers with higher priority must not be placed beneath those with lower priority (Ji et al., 2015).

A separate group of publications related to container yard storage focuses on methods for optimizing container placement and movement. These methods can be classified into three main categories: optimization-based approaches (including exact methods for small-scale problems, heuristics, and metaheuristics), artificial intelligence-based approaches, and simulation-based approaches.

Among the metaheuristic algorithms used to solve the container yard storage problem, researchers have applied methods such as Tabu Search (Jiang et al., 2013; Casey & Kozan, 2012), Simulated Annealing (Zhen, 2014; Fu et al., 2007; Kang et al., 2006) Genetic Algorithms (Ji et al., 2015; Yang & Kim, 2006) as well as hybrid approaches—such as the one proposed in Moussi et al. (2015), where a combination of Simulated Annealing and Ant Colony Optimization was used to solve the problem. Among these methods, Genetic Algorithms (GA) have gained the most popularity due to their superior performance compared to other approaches.

Simulation-based methods, such as Discrete Event Simulation (DES), have been used less frequently. For example, in Borgman et al. (2010) this approach was applied to model container storage operations under uncertain pickup times, analyzing the trade-off between storage location and the number of relocations. Similarly, in Dekker et al. (2006) the

authors conducted a comparative analysis of different storage strategies within an automated system.
Artificial Intelligence (AI) has been used to address the container storage problem in only a few studies to date. Examples of such applications can be found in Hottung et al. (2020); Rekik & Elkosantini (2019).
A review of the literature in the field of container yard storage indicates a noticeable gap in studies addressing the impact of the number of stacking layers on the cargo handling time of external transport vehicles. As discussed in Chapter 1, identifying this relationship is particularly important for designing the container yard layout and selecting the appropriate number of handling equipment units.

4. Simulation model

4.1. Input data and assumptions for the simulation study

To analyze the research problem concerning the process of loading an intermodal train with containers stored in a terminal yard, simulation modeling tools were employed. The objective of the study was to determine the impact of the number of container stacking layers in a land-based rail intermodal terminal yard on the operational and energy efficiency of the handling process. The experiments focused on identifying the relationship between the number of containers stacked in layers and parameters such as operation time, the number of crane handling operations, crane energy consumption, and the distances traveled by the handling equipment.
The simulations were conducted using a simulation model of an intermodal terminal developed in FlexSim (version 2024). The model incorporated the basic elements of the terminal's infrastructure (storage yard, railway track), superstructure (RTG container crane), as well as crane parameters, container characteristics, and the strategy for container loading and reshuffling within the yard area. (Fig. 3).
As part of the study, five container yard layout variants were analyzed, in which containers were stacked in a maximum of one, two, three, four, or five layers. Container stacks were arranged in up to six rows, resulting in a yard approximately 485 meters long and 15.5 meters wide. The nominal capacity of the storage yard (with containers stored in a single layer) is 324 TEU. For the purposes of the study, it was assumed that the yard would be filled to 80% capacity in each variant (Table 1). Three types of containers can be stored in the yard: 20ft, 30ft, and 40ft. Container placement within the yard was randomly generated for each simulation experiment.
It was assumed that the maximum allowable gross weight of each container type was also random but did not exceed: 23.2 tons (20ft), 25.4 tons (30ft), and 30.48 tons (40ft). The study considered the impact of container weight (W_C) on the lifting and lowering speed of the RTG crane. Based on research presented in the literature (Papaioannou et al., 2017; Kłodawski et al., 2024a), it was assumed that the lifting speed of the container (V_{CL}) would be equal to its lowering speed (V_{CL}) and would be determined using the relationship described in Equation (1):

$$V_{CL} = V_{CD} = -0{,}684 \cdot W_C + 53{,}368 \quad (1)$$

The loading track, where railcars are positioned for loading, is long enough to accommodate 30 railcars. Each railcar has a total capacity of up to 3 TEU (60 ft). This means that each railcar can be loaded with containers in the following combinations: 20 ft + 40 ft, 30 ft + 30 ft, 20 ft + 30 ft, or 20 ft + 20 ft + 20 ft. Container loading is carried out using an RTG crane, with its main operational parameters presented in Table 2.

4.2. Simulation experiment procedure

After the simulation model is launched, railcars are randomly positioned on the loading track along with a defined locking pin configuration (the pin configuration determines the types of containers that can be loaded onto individual railcars). Next, containers are placed within the storage yard according to the required yard occupancy, the assumed number of containers of each type, and the maximum number of stacking layers. From among the containers placed in the yard, a subset is randomly selected to be loaded in the next stage. These selected containers may be located at any stacking layer.
The model assumes a constraint that each container selected for loading must have a compatible slot available on one of the randomly positioned railcars. Once the containers in the yard and the railcars on the loading track are prepared, the RTG crane begins the loading process.

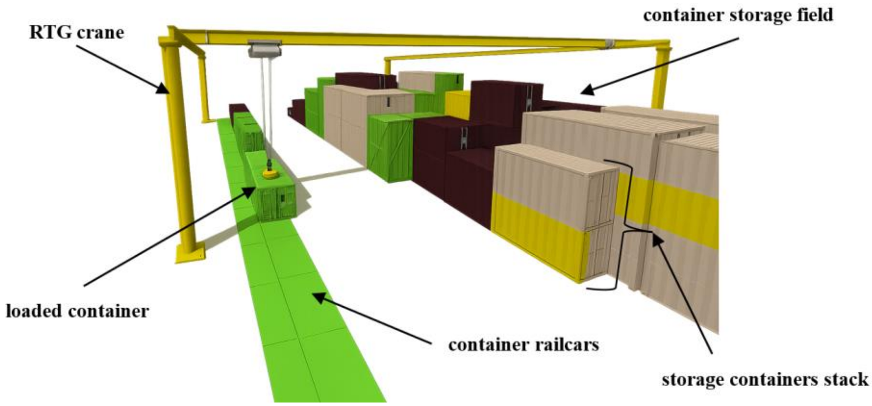

Fig. 3. Container loading front in FlexSim simulation model

Table 1. Number of containers stored in the yard in each simulation variant

Variant	Number of stacking layers	Yard utilization	Number of containers in the yard
1	1	80%	260
2	2		518
3	3		777
4	4		1035
5	5		1296

Table 2. Operational parameters of RTG crane used in simulation

Parameter	Value
Gantry speed [m/sec]	0,66
Gantry acceleration [m/sec2]	1
Trolley speed [m/s]	1,16
Trolley acceleration [m/sec2]	1
Hoist lift speed [m/sec]	See equation 1
Hoist drop speed [m/sec]	See equation 1
Hoist acceleration [m/sec2]	1
Lift height [m]	10,5
Container pick-up time [sec]	5
Container put off time [sec]	10

The sequence of tasks performed by the crane, understood as the order in which containers are picked up and assigned to railcars is based on a greedy algorithm. A simplified version of this algorithm in pseudocode is presented in Fig. 4.

If the container to be retrieved is located at the bottom of a stack, the containers above it must first be removed and placed in the nearest available location. It is assumed that reshuffled containers may be placed in stacking layers higher than the originally defined maximum for the given scenario, but not exceeding the fifth layer. It must also be noted that containers may only be placed onto stacks composed of containers of the same type (20ft, 30ft, or 40ft).

4. Simulation results

To address the defined research problem, five different container yard layout variants were analyzed, involving 1, 2, 3, 4, and 5 stacking layers (Table 1). For each variant, fifteen replications were performed, and average values were calculated for selected parameters and performance indicators of the loading process. These included: the total distance traveled by the crane, the total loading time, the energy required for the loading process, as well as the number and duration of container-handling operations.

K – set of containers to be loaded (each with a type and position (x, y))
W – set of railcars (each with a position (x, y) and a list of supported container types)
Y – yard layout with stacking information
S – set of storage location in yard
p – current position of the crane (x, y)

```
Procedure LoadContainers(K, W, Y, p)
//Start the loading process.
While (K is not empty) do:
    Select container k from K that is nearest to the current crane position p.
    If (container k is not on top of its stack in Y) then:
        For each (container k' located above k) do:
            Find the nearest available location s in the yard (where s ∈S).
            Move crane to k', pick it up, and transport it to s.
            Place container k' at s.
            Update crane position: p ← position(s).
        End for
    End if
    Move crane to container k and pick it up.
    Update crane position: p ← position(k).
    Find the nearest railcar w (where w ∈W) that supports the type of
    container k.
    Move container k to railcar w.
    Place container k on railcar w.
    Update crane position: p ← position(w).
    Remove container k from set K.
End while
End Procedure
```

Fig. 4. Pseudocode of containers loading procedure

The total distance traveled by the RTG crane (L_{CRANE}) is calculated as the sum of the distances covered by its structural components in all three movement axes—gantry, trolley, and hoist.
The loading time (T_{CRANE}) is defined as the time difference between the placement of the last container onto a railcar and the start of the loading process for the first container. This duration is directly influenced by the travel distances, the speeds of the individual crane components, and the container-handling times (Table 2). In cases where the crane moves simultaneously in multiple directions, the duration of the longest movement is taken into account.
To estimate the crane's energy consumption, key motion parameters are recorded during the simulation. The total energy consumption is calculated as the sum of energy used by the gantry drive system (E^X_{CRANE}), trolley drive system (E^Y_{CRANE}) and hoist drive system (E^Z_{CRANE}) minus the energy recovered during crane operation (E^R_{CRANE}):

$$E_{CRANE} = E^X_{CRANE} + E^Y_{CRANE} + E^Z_{CRANE} - E^R_{CRANE} \quad (2)$$

The formulas used to estimate the components of equation (1) are based on actual measurement data from an RTG crane, as presented in Papaioannou et al. (2017), where eight days of crane operation under varying workload conditions were analyzed. Based on this data, the relationships expressed in equations (3–5) were derived:

$$E^X_{CRANE} = S_G \cdot \left(\frac{64{,}34 \cdot T_X}{3600} + 24{,}37\right) \quad (3)$$

$$E^Y_{CRANE} = S_T \cdot \left(\frac{64{,}34 \cdot T_Y}{3600} + 24{,}37\right) \quad (4)$$

$$E_{CRANE}^{Z} = S_H \cdot (64{,}34 \cdot (\frac{T_{ZUL}+T_{ZUE}}{3600}) + 24{,}37) \quad (5)$$

Where:
T_X – travel time of the crane gantry
T_Y – travel time of the crane trolley
T_{ZUE} – hoist operation time (lifting) without load
T_{ZUL} – hoist operation time (lifting) with container
S_G – energy consumption coefficient for gantry travel (0,31)
S_{GR} – energy recovery coefficient for gantry travel (0,81)
S_T – energy consumption coefficient for trolley movement (0,07)
S_H – energy consumption coefficient for hoist operation (0,62)
S_H – energy recovery coefficient for hoist operation (0,037)

The conducted simulation experiments also accounted for the possibility of energy recovery during gantry and hoist movements. According to the findings presented in Papaioannou et al. (2017) up to 81.5% of the energy consumed by the hoist can be recovered during operation. In the case of gantry deceleration, approximately 3.7% of the energy used can be recovered. Therefore, in the present analysis, energy recovery (E_{CRANE}^{R}), was included and estimated based on the relationships defined in equations (6–8):

$$E_{CRANE}^{R} = E_{CRANE}^{RX} + E_{CRANE}^{RZ} \quad (6)$$

$$E_{CRANE}^{RX} = S_{GR} \cdot S_G \cdot (\frac{64{,}34 \cdot T_X}{3600} + 24{,}37) \quad (7)$$

$$S_{HR} \cdot S_H \cdot (64{,}34 \cdot (\frac{T_{ZDL}+T_{ZDE}}{3600}) + 24{,}37) \quad (8)$$

For the purposes of the study, the simulation also records the total number of container-handling operations performed by the crane during loading (N_{CHO}), including the number of operations related to picking up containers designated for loading (N_{LCO}) and those related to reshuffling containers located on top of the container to be loaded (N_{SCO}). Additionally, the durations of these operations are estimated: (T_{CHO}, T_{LCO}, T_{SCO}).

For each defined experimental variant, 15 simulation runs were conducted, during which the slot configurations on the railcars and the placement of containers in the yard were randomly generated. As a result, the locations of containers designated for loading were also random and could appear in any of the analyzed stacking layers.

The results of all 15 replications for each variant were analyzed in terms of variability, and average values were calculated for further analysis. The results obtained in this way are summarized in Table 3.

A preliminary analysis of the obtained results clearly indicates that as the number of container stacking layers in the yard increases, the total distance traveled by the crane, the amount of energy consumed, and the total loading time of the intermodal train also increase Fig. 5. However, what is particularly important in this case is identifying the factors contributing to these increases and understanding to what extent they grow with the number of stacking layers. The increase in loading time and energy consumption is directly related to the distances traveled by the crane (Table 3), as well as the type and number of operations performed by the crane (Fig. 6). As the number of container stacking layers increases, the number of reshuffling operations also rises. With two stacking layers, these operations account for nearly 30% of all crane movements, whereas with five stacking layers, reshuffling represents over 61% of all container-handling operations (Fig. 7).

Table 3. Simulation results for different numbers of container stacking layers

Parameter	Number of containers stacking layers				
	1	**2**	**3**	**4**	**5**
Distance (L_{CRANE}) [m]	7829,68	8485,26	9796,76	9921,36	11358,60
Loading Time (T_{CRANE}) [minutes]	145,55	165,15	201,68	206,72	244,90
Energy (ECRANE) [kWh]	53,32	57,25	67,73	68	78,53
Number of Container Handling Operations (N_{CHO})	54,00	77,00	99,00	117,00	139,00
Number of Container Loading Operations (N_{LCO})	54,00	54,00	54,00	54,00	54,00
Number of Container Relocation Operations (N_{SCO})	0,00	23,00	45,00	63,00	85,00
Container Loading Operations Time (T_{LCO})	145,55	128,09	137,36	128,46	129,48
Container Relocation Operations Time (T_{SCO})	0,00	37,06	64,32	78,26	115,42

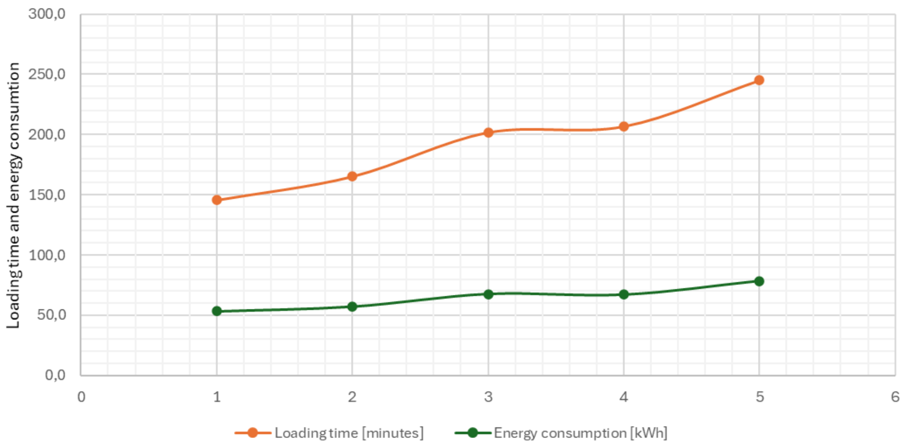

Fig. 5. Results of loading time and Energy consumption by RTG crane

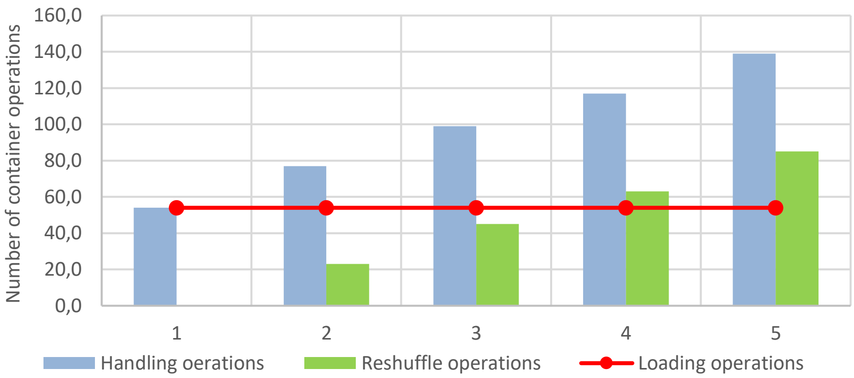

Fig. 6. Number and types of operations performed by the crane during train loading

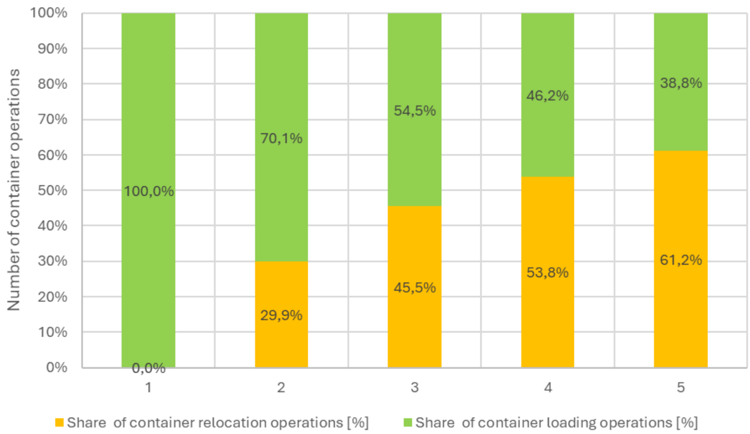

Fig. 7. Share of loading and reshuffling operations

A similar trend can be observed in the duration of individual operations (Fig. 8). In the case of one stacking layers, reshuffling time accounts for approximately 22.4% of the total train loading time, whereas with five stacking layers, it amounts to nearly half of the loading time (47.1%). It can therefore be clearly stated that reshuffling time is the main factor contributing to the extension of loading duration and the increase in energy consumption by the crane.

However, energy consumption does not grow at a slower rate than loading time (Fig. 9). This is due to the fact that as the number of reshuffled containers increases, the amount of energy recovered by the crane during container lowering also increases. As a result, the total energy demand from external sources decreases (see Equation 2).

Thus, it can be concluded that the energy efficiency of the process does not improve linearly with the number of container-handling operations. Energy recovery contributes to making the process more sustainable.

It is therefore worth noting how loading time, distance traveled, and energy consumption increase with the rising number of container stacking layers in the storage yard (Table 4). For each of the analyzed parameters, the most significant jumps occur between layers 1 and 2, and between layers 4 and 5. When deciding on the number of stacking layers, variants 2 and 4 should be considered in cases where saving yard space is a priority. In these scenarios (i.e., choosing between variant 1 and 2 or variant 3 and 4), significant gains in storage space can be achieved with only a minor increase in energy consumption and loading time (Table 4).

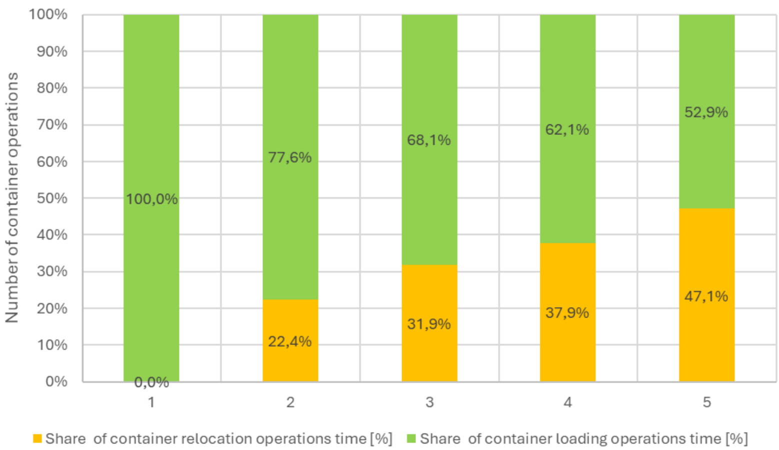

Fig. 8. Share of time spent on loading and reshuffling operations

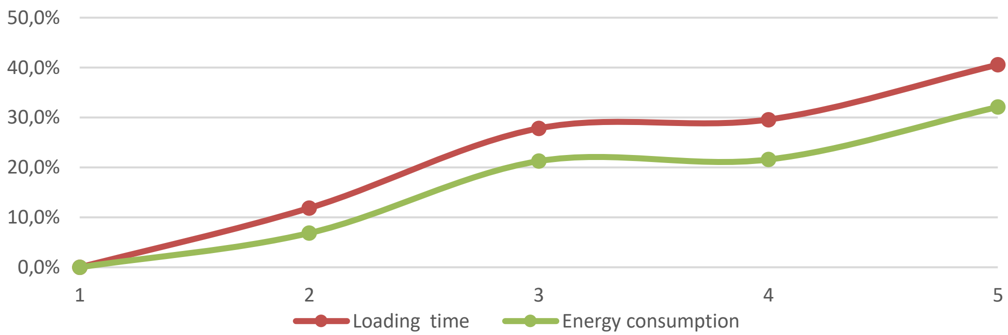

Fig. 9. Percentage increase in loading time and energy consumption in each variant compared to variant 1

Table 4. Percentage increase in loading time and energy consumption in each variant compared to variant 1

Parameter	Stacking layers				
	1	2	3	4	5
Distance	-	7,7%	20,1%	21,1%	31,1%
Loading time	-	11,9%	27,8%	29,6%	40,6%
Energy consumption	-	6,9%	21,3%	21,6%	32,1%

An obvious conclusion is that as the number of stacking layers increases, the surface area required for container storage decreases proportionally. This results in a higher storage capacity of the yard in terms of the number of containers it can accommodate.

The conducted study also revealed that storing containers closely together in a small area does not reduce loading time—in fact, it has the opposite effect. When containers are not spread along the loading track but instead clustered in one location, the crane's loading cycles become longer, and the distances traveled by the crane increase.

5. Summary

The conducted simulation study enabled a detailed analysis of the impact of the number of container stacking layers in an intermodal terminal yard on intermodal train loading time and crane energy consumption. The results clearly confirm that an increase in stacking layers leads to a significant rise in total loading time, crane travel distances, and overall energy demand. This is primarily due to the growing number of reshuffling operations, which at five stacking layers account for over 60% of all crane movements and nearly half of the total loading time.

The analysis showed that the increases in cycle time and energy consumption are non-linear, with the rate of change varying depending on the specific number of stacking layers. The most significant changes were observed between layers 1 and 2, and 4 and 5. Importantly, although the number of crane operations increases, energy consumption does not grow proportionally, thanks to the crane's energy recovery mechanism during container lowering. This contributes to making the process more energy-efficient, even though it remains less time-efficient.

From a practical perspective, the results of the study can serve as decision support for terminal operators when determining the optimal number of stacking layers.

While it may have been intuitively assumed that higher stacking increases loading time and energy consumption, there has been a lack of studies quantifying how these changes occur and identifying which process components are most responsible. The simulation developed in the FlexSim environment has proven to be an extremely valuable research tool for analyzing such complex logistics processes. It enables not only a quantitative evaluation of the effects of organizational changes, but also provides a robust foundation for making well-informed operational and strategic decisions.

References

1. Ambrosino, D., Asta, V., & Crainic, T. G. (2021). Optimization challenges and literature overview in the intermodal rail-sea terminal. *Transportation Research Procedia*, 52, 163–170. https://doi.org/10.1016/j.trpro.2021.01.020.
2. Borgman, B., van Asperen, E., & Dekker, R. (2010). Online rules for container stacking. *OR Spectrum*, 32(3), 687–716. https://doi.org/10.1007/s00291-010-0205-4.
3. Bruns, F., & Knust, S. (2012). Optimized load planning of trains in intermodal transportation. *OR Spectrum*, 34(3), 511–533. https://doi.org/10.1007/s00291-010-0232-1.
4. Brzeziński, M., & Pyza, D. (2021). Carbon dioxide emission from diesel engine vehicles in intermodal transport. *Transport*, 36(3), 246–259. https://doi.org/10.3846/transport.2021.15484.
5. Caserta, M., Schwarze, S., & Voß, S. (2012). A mathematical formulation and complexity considerations for the blocks relocation problem. *European Journal of Operational Research*, 219(1), 96–104. https://doi.org/10.1016/j.ejor.2011.12.039.
6. Casey, B., & Kozan, E. (2012). Optimising container storage processes at multimodal terminals. *Journal of the Operational Research Society*, 63(8), 1126–1142. https://doi.org/10.1057/jors.2011.113.

7. Zhou, C., Wang, W., & Li, H. (2020). Container reshuffling considered space allocation problem in container terminals. *Transportation Research Part E: Logistics and Transportation Review*, 136, 101882. https://doi.org/10.1016/j.tre.2020.101882.
8. Dekker, R., Voogd, P., & van Asperen, E. (2006). Advanced methods for container stacking. *OR Spectrum*, 28(4), 563–586. https://doi.org/10.1007/s00291-006-0038-3.
9. Komisja Europejska. (2011). Biała księga. Plan utworzenia jednolitego europejskiego obszaru transportu – dążenie do osiągnięcia konkurencyjnego i zasobooszczędnego systemu transportu. [Online]. Dostępne na: https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX%3A52011DC0144.
10. Feng, Y., Song, D. P., & Li, D. (2022). Smart stacking for import containers using customer information at automated container terminals. *European Journal of Operational Research*, 301(2), 502–522. https://doi.org/10.1016/j.ejor.2021.10.044.
11. Fu, Z., Li, Y., Lim, A., & Rodrigues, B. (2007). Port space allocation with a time dimension. *Journal of the Operational Research Society*, 58(6), 797–807. https://doi.org/10.1057/palgrave.jors.2602192.
12. Gnap, J., Senko, Š., Drličiak, M., & Kostrzewski, M. (2021). Modeling of time availability of intermodal terminals. *Transportation Research Procedia*, 55, 442–449. https://doi.org/10.1016/j.trpro.2021.07.007.
13. Hottung, A., Tanaka, S., & Tierney, K. (2020). Deep learning assisted heuristic tree search for the container pre-marshalling problem. *Computers & Operations Research*, 113, 104781. https://doi.org/10.1016/j.cor.2019.104781.
14. https://obserwatorlogistyczny.pl/2024/04/05/baltic-hub-bije-kolejny-rekord-tysiace-ciezarowek-i-kontenerow-obsluzone-w-mgnieniu-oka/ (access: 28.03.2025)
15. Izdebski, M., Jacyna, M., Klimek, P., Jacyna-Gołda, I., & Vašek, R. (2019). Decision-making problems of designing database in the aspect of planning transport of cargoes by intermodal transport. *MATEC Web of Conferences*, 294, 04005. https://doi.org/10.1051/matecconf/201929404005.
16. Jachimowski, R., Szczepański, E., Kłodawski, M., Markowska, K., & Dąbrowski, J. (2018). Selection of a container storage strategy at the rail-road intermodal terminal as a function of minimization of the energy expenditure of transshipment devices and CO_2 emissions. *Rocznik Ochrona Środowiska*, 20, 965–988.
17. Ji, M., Guo, W., Zhu, H., & Yang, Y. (2015). Optimization of loading sequence and rehandling strategy for multi-quay crane operations in container terminals. *Transportation Research Part E: Logistics and Transportation Review*, 80, 1–19. https://doi.org/10.1016/j.tre.2015.05.004
18. Jiang, X., Chew, E. P., Lee, L. H., & Tan, K. C. (2013). Flexible space-sharing strategy for storage yard management in a transshipment hub port. *OR Spectrum*, 35(2), 417–439. https://doi.org/10.1007/s00291-012-0308-1
19. Kang, J., Ryu, K. R., & Kim, K. H. (2006). Deriving stacking strategies for export containers with uncertain weight information. *Journal of Intelligent Manufacturing*, 17(4), 399–410. https://doi.org/10.1007/s10845-005-0013-x
20. Kłodawski, M., Jachimowski, R., & Chamier-Gliszczyński, N. (2024). Analysis of the overhead crane energy consumption using different container loading strategies in urban logistics hubs. *Energies*, 17(5), 985. https://doi.org/10.3390/en17050985
21. Kłodawski, M., Nehring, K., Jachimowski, R., & Lipińska, J. (2024). The impact of the intermodal terminal operation strategy on container train loading duration. *Transport Problems*, 19(2), 163–176. https://doi.org/10.20858/tp.2023.19.2.13
22. Krześniak, M., Jacyna, M., Pryciński, P., Murawski, J., & Bańka, M. (2022). Business environment of rail transport in the context of the value chain. *Zeszyty Naukowe. Transport – Politechnika Śląska*, 116, 179–195. https://doi.org/10.20858/sjsutst.2022.116.11
23. Lee, D. H., Jin, J. G., & Chen, J. H. (2012). Terminal and yard allocation problem for a container transshipment hub with multiple terminals. *Transportation Research Part E: Logistics and Transportation Review*, 48(2), 516–528. https://doi.org/10.1016/j.tre.2011.09.004

24. Moussi, R., Euchi, J., Yassine, A., & Ndiaye, N. F. (2015). A hybrid ant colony and simulated annealing algorithm to solve the container stacking problem at seaport terminal. *International Journal of Operational Research*, 24(4), 399–422. https://doi.org/10.1504/IJOR.2015.069695
25. Papaioannou, V., Pietrosanti, S., Holderbaum, W., Becerra, V. M., & Mayer, R. (2017). Analysis of energy usage for RTG cranes. *Energy*, 125, 337–344. https://doi.org/10.1016/j.energy.2017.02.122
26. Rekik, I., & Elkosantini, S. (2019). A multi-agent system for the online container stacking in seaport terminals. *Journal of Computational Science*, 35, 12–24. https://doi.org/10.1016/j.jocs.2019.06.003PMC
27. Van Asperen, E., Borgman, B., & Dekker, R. (2011). Evaluating impact of truck announcements on container stacking efficiency. *Flexible Services and Manufacturing Journal*, 25(4), 543–556. https://doi.org/10.1007/s10696-011-9108-1
28. Van Lancker, M., Van den Berghe, G., & Wauters, T. (2018). Intermodal rail-road terminal operations. *Welcome to ORBEL 32*, 34(3), 93.
29. Woo, Y. J., & Kim, K. H. (2011). Estimating the space requirement for outbound container inventories in port container terminals. *International Journal of Production Economics*, 133(1), 293–301. https://doi.org/10.1016/j.ijpe.2010.04.032jsdtl.sciview.net
30. Yang, J. H., & Kim, K. H. (2006). A grouped storage method for minimizing relocations in block stacking systems. *Journal of Intelligent Manufacturing*, 17(4), 453–463. https://doi.org/10.1007/s10845-005-0015-8
31. Zabielska, A., Jacyna, M., Lasota, M., & Nehring, K. (2023). Evaluation of the efficiency of the delivery process in the technical object of transport infrastructure with the application of a simulation model. *Eksploatacja i Niezawodność*, 25(1), 146–155. https://doi.org/10.17531/ein.2023.1.15
32. Zhen, L. (2014). Container yard template planning under uncertain maritime market. *Transportation Research Part E: Logistics and Transportation Review*, 69, 199–217. https://doi.org/10.1016/j.tre.2014.05.013