УДК 621.8 DOI: 10.20998/2078-6840.2024.2.03

V. KOVALENKO, O. TURCHYN, V. ALIEKSIEIEV, V. STRYZHAK, M. STRELKOV; O. POLIAKOV

IMPROVING THE ENERGY EFFICIENCY OF CONTAINER STACK ASSEMBLY-DISASSEMBLY OPERATIONS AT CONTAINER TERMINAL YARD

Container storage in the yard decouples fluctuating incoming and outgoing container flows on container terminals and is an important element of the terminal process chain. The efficiency of handling operations in storage area, such as stacking and extraction of containers, has a significant influence on the overall terminal performance. In this respect, optimization of these processes, such as minimization of numerous unproductive movements of surrounding containers, which impede their immediate accessibility, is of particular interest. The relevant problems are well developed in mathematical terms. Optimizing algorithms mainly involve the use of heuristic/hyper-heuristic rules. However, only a small amount of this work focuses on the energy aspect of this problem. This article focuses on the most general approaches to minimizing energy consumption in container stacking operations. The performed analysis of energy consumption of the yard RTG crane for different working movements showed the prevalence of energy consumption when lifting containers. In this regard, attention is drawn to the importance of including in the optimization analysis in addition to the process of retrieving containers from the stack - the process of stack formation. Minimizing the level of the stack's center of gravity just before disassembling can be considered as a goal. Due to the complexity of the problem, an attempt to simplify the rules of container placement is made, taking into account some features of the energy approach. A possible generalized version of the arrangement scheme and the rule of removal of all containers are considered.

Keywords: Container Relocation Problem, energy efficiency, RTG crane

В. О. КОВАЛЕНКО, О. В. ТУРЧИН, В. І. АЛЄКСЄЄВ, В. В. СТРИЖАК, М. Б. СТРЕЛКОВ, О. А. ПОЛЯКОВ

ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ ОПЕРАЦІЙ ЗІ ЗБИРАННЯ-РОЗБИРАННЯ ШТАБЕЛІВ КОНТЕЙНЕРІВ НА МАЙДАНЧИКУ КОНТЕЙНЕРНОГО ТЕРМІНАЛУ

Зберігання контейнерів на майданчику дозволяє відокремити коливання вхідних і вихідних потоків контейнерів на терміналах і є важливим елементом ланцюга процесів терміналу. Ефективність операцій у зоні зберігання, таких як штабелювання та вилучення контейнерів, значно впливає на загальну продуктивність терміналу. Оптимізація цих процесів, зокрема мінімізація зайвих переміщень контейнерів, які перешкоджають доступу до них, має велике значення. Хоча ці проблеми добре описані математично, лише незначна частина робіт фокусується на енергетичному аспекті. У статті розглядаються загальні підходи до зниження енергоспоживання під час операцій штабелювання. Аналіз енергоспоживання крана RTG показав, що основна частина енергії витрачається на підйом контейнерів. Тому доцільно включити в оптимізацію не тільки процес вилучення контейнерів, але й процес їхнього розміщення. Мета – мінімізувати висоту центра ваги штабеля перед його розбиранням. Через складність задачі пропонується спрощення правил розміщення контейнерів з урахуванням енергетичного підходу, а також загальна схема їхнього розташування і видалення.

Ключові слова: проблема переміщення контейнерів, енергоефективність, кран, RTG

Introduction. Marine container terminals are one of the key elements of modern intermodal logistics chains. This paper considers the most general approaches to solving the problem of energy efficiency of container stacking operations by gantry cranes. These issues are especially relevant for Ukrainian ports operating in conditions of acute energy deficit.

The processes of container handling at the container terminal are shown in fig. 1.

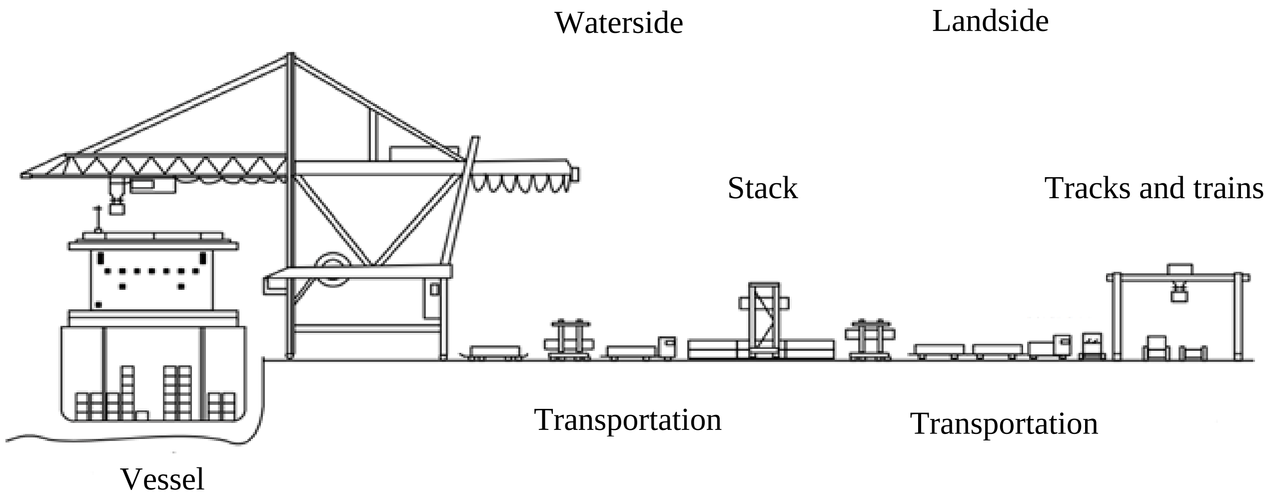


Fig. 1 – Container handling processes at a container terminal [1]

The central position of the yard is such not only geometrically, but also in functional and distributive terms. It is an object of creative rethinking, which is currently undergoing changes on a conceptual level. An example is the ongoing design and installation work of rack (high bay) storage facilities (see Figure 2).

It is expected that this will result in a multiple improvement in all key warehouse utilization indicators. In the context of this paper, the extremely high level of energy efficiency achieved is important. For this purpose, the power supply is provided by solar panels placed on the warehouse roof. The stacker cranes operating the shelving units are lightweight, so that the energy consumption for acceleration and friction is significantly reduced. A DC power supply system with energy recovery and energy storage is used.

a **b** **c**

Fig. 2 – BOXBAY high bay store for containers in Dubai (stage of sectional commissioning): (a). First commercial order [2] (b). High-Bay Container Storage. Konecranes (project) [3] (c)

The following is a minimal summary of the functional characteristics of a storage yard used to reconcile flows on both sides of the yard. Cargo flows on the water and land sides of the yard have different intensities, irregularities, and temporal distribution. The developers of the BOXBAY project - SMS group & DP World - offer different warehouse concepts for the land and water sides: "Side-grid" and "Top greed" respectively. The flow on the water side is characterized by peaks during loading/unloading periods.

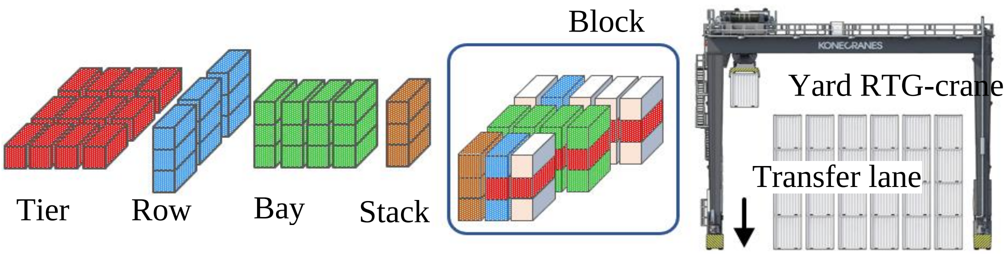
Parallelization of the stack loading/unloading process provides the greatest transportation intensification. In the variant of front loading/unloading the distributing element is one crane for several cars. To ensure high speed of horizontal movements of the crane and its trolley without loss of positioning accuracy, the Gottwald cranes in the ports of Amsterdam and Antwerp have the load holder (spreader) fixed on a rigid column (Fig. 3). Side loading/unloading of stacks is more common. In this case paralleling of the cargo flow is ensured by simultaneous operation of many cranes, and a chain of machines on one track or Multi Trailer System is used for transportation.

a b c

Fig. 3 – Trucks drivers at terminal in the Port of Antwerp-Bruges:
(a) [4], [5]. Trucks in Lower Mainland ports (b) [6]. Multi Trailer System (c) [7]

The traffic on the land side is generally less intensive. When working with a stack, it is often necessary to access containers that are overlapped by other containers. This requires additional repositioning, the number of which should be reduced. A considerable amount of research has been devoted to the problem of removing containers from a stack. In this paper we consider the energy aspect of this problem.

The main terms used in this paper are explained in Fig. 4.



a b

Fig. 4 – Interpretation of the main terms characterizing the container block structure:
(a) [8]. Gantry yard cranes used for container block maintenance (b) [9]

Optimization of the containers removing procedure from the stack for the minimum time is called the Container Relocation Problem (CRP). The interest is related to the possibility to significantly improve the quality of operations in the warehouse, practically, without modernization and reconstruction of the existing equipment, without significant changes in the technological process.

To solve the CRP, heuristic relocation rules (RRs) described algorithmically are successfully used. In the most complex cases, the analysis of branched sequences of actions is performed with culling of the least effective variants according to the evaluation of the efficiency criterion. To realize the approach, object programming can be used in a language that provides increased speed of calculations. Fig. 5 shows one of the possible approaches as an example - a sequence of permutations chosen after rejecting suboptimal branches of actions [8]. As can be seen, container 1 needs to be moved through 2 neighboring containers.

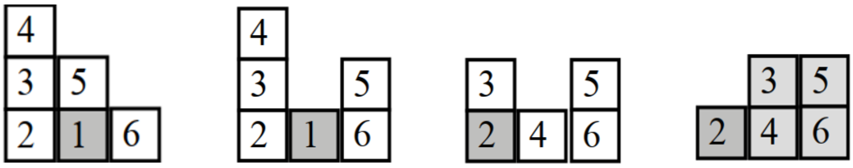


Fig. 5 – Examples of heuristic “beam search” rules for moving a container from Bay [8]

At present, the CRP task is quite well developed. A large number of relevant studies are available. Above mentioned research [8] utilizes the apparatus of hyper-heuristics, which allows several simpler heuristics to be combined in a particular way. These are mainly over-arrangements in separate transverse rows.

Of the works known to us, we can single out some that are only roughly related to the stacking energy problem. Work [10] focuses on the movement of containers between stacks. In the context of the research topic, only 2 works can be singled out – [11] and [12]. In both papers data on the average energy consumption of diesel-driven rubber tired yard gantry cranes (RTG) in ports of Long Beach and Los Angeles for the year 2009 are used as input information. The work [12] is a continuation and development in algorithmic terms of the topic formulated in [11]. Hyperheuristics are used to solve the corresponding mathematical problem. A full description of the analyzed problem is given, for example, in [13]. Briefly, these issues have been covered in the paper [14].

This study is intended to supplement some aspects of the production plan that have been insufficiently considered. It is necessary to clarify the energy consumption of modern crane models, to find out the costs of stack loading, to consider variants of container arrangement schemes favorable for loading and unloading.

In CRP problems, a known but arbitrary initial filling of a stack row is usually considered. This filling can be varied. A number of other related problems are also known, such as finding an ideal scheme of initial stack structuring by blocks - Block allocation problem (BAP) or for a single cross row - Slot allocation problem (SAP).

Research Methodology.

In this article, a problem from the group of SAP is considered. It is connected with the revealed necessity to consider energy inputs not only during stack disassembly, but also during its formation, and the most natural way to take into account criteria for both processes is optimization of the arrangement scheme.

The problem is to find the optimal container arrangement scheme and the corresponding stack assembly-disassembly sequence that minimize energy consumption. The masses and sequence numbers of the retrievals are assumed to be known and unchanged from the beginning of the stack formation to complete disassembly. Side unloading of the stack is considered.

Resistances at working movements.

Rubber-tired yard gantry cranes (RTG, see Fig 6) are considered in a fully electrically driven version, which is provided by equipping the working areas with stationary trolleys, cable tracks, as well as switching points for cable current supply [15].

The masses of the structural elements and the speeds of the working movements are very close to those of the leading cranes. We used the catalog parameters of the latest Konecranes cranes [9]. Energy consumption during the working movements was determined according to the methods generally accepted in the crane industry [16], [17].

It was taken into account that most manufacturers equip cranes of this type with telescopic spreaders, made by specialized manufacturers, what is necessary for the possibility of alternate work with containers 20', and 40'. The weight of the spreader specified in the Konecranes brochure is 8 tons [9]. The weights of spreaders produced by different companies do not differ much from each other.

Fig. 6 – RTG Yard crane [18]

Calculations were performed for the smallest and largest working displacements. Bay of 6 tiers and 8 stacks with 20' and 40' containers was considered (Table 1).

The displacements were specified stepwise in 3 directions. Steps correspond to container dimensions + gaps in rows and top required for safe side and top transfer.

The work spent on lifting the bodies in the potential field and on overcoming the resistance during the movement was taken into account. Additional friction losses in the rope reeving system and on the drum - specific for this mechanism - were taken into account for the lifting mechanism. Other losses were neglected because, in the end, relative estimates are of interest, and the efficiencies of gearboxes and couplings for all types of mechanisms are close in values.

Table 1 – Working movements of containers

Container size	**Direction**	**No Pitches**	**Size**	**Clearence**	**Moving**
			m		
20’	**H**	**1**	2,59	1,04	3,626
		6	2,59	1,04	16,576
	B	**1**	2,44	0,4	2,84
		8	2,44	0,4	19,92
	L	**1**	6,05	0,2	6,25
40’		**1**	12,19	0,2	12,39

The rolling resistance coefficient and edge friction in the steel wheel-rail pair were taken into account when determining the resistance to trolley movement. For the crane, the resistance for rubber wheels of class A (6.6 kg/t) was taken into account in accordance with Regulation (EC) No 1222/2009.

The calculation results are given in Table 2.

Resistances from the wind and slope of the track were not taken into account due to the different directionality of the frequently performed movements (if during movement in one direction these influences impede the movement, in the opposite direction they promote it).

The works done in lowering and in breaking were not taken into account for the following reasons. These movements are performed in generator mode using a squirrel cage motor powered by a frequency converter. In this case, mechanical energy is converted into electrical energy, which is utilized as heat, mainly at the braking resistors. The additional current consumed from the electrical grid by the stator, which is necessary to maintain the generator mode, is small and was neglected.

Table 2 - Energy expenditure during performance of work movements

		Working Speeds, m/min	Working Speeds, m/s	Kinetic energy, kJ	No pitches	Resistance work, kJ	Total energy consumption, kJ	No pitches	Resistance work, kJ	Total energy consumption, kJ
Hoisting	Full load	31	0,52	5	**1**	1523	**1528**	**6**	6962	**6967**
	0,5 Full load			3		981	**985**		4486	**4490**
	Empty container	62	1,03	6		440	**446**		2011	**2017**
	Only spreader			4		301	**305**		1375	**1379**
Trolleying	Full load	70	1,17	43		17	**60**	**8**	118	**161**
	0,5 Full load			33		13	**46**		91	**124**
	Empty container			23		9	**32**		64	**87**
	Only spreader			21		8	**29**		57	**78**
Gantrying 20’	Full load	135	2,25	464		108	**572**			
	0,5 Full load			427		99	**527**			
	Empty container			391		91	**482**			
	Only spreader			382		89	**470**			
Gantrying 40’	Full load			464		214	**678**			
	0,5 Full load			427		197	**624**			
	Empty container			391		180	**571**			
	Only spreader			382		176	**558**			

Conclusions on the results of preliminary calculations. There is a pronounced general prevalence of energy consumption in lifting movements. Movements to the side of the stack (trolley movement) are much less energy-consuming at any combinations of loads and movement steps. When lifting an empty spreader to 1 level of the stack, the crane movement costs will be higher, but lifting an empty spreader to 2 levels is, in fact, as costly as moving a crane with a container with maximum load on a stroke equal to the length of the container. The revealed basic regularity is taken into account in the future when making different schemes of stack formation. The results obtained, in general, agree with the data used in [11, 12].

Simple stack formation schemes and preliminary results.

Preliminarily, we considered the problem for one column only. Only vertical displacements were taken into account. The displacement diagrams for a three-level stack are shown in fig. 10. The top row of images shows the removal of containers, some of which are temporarily placed on the top level (the lowering of this level as the containers are removed is not shown).

As a result of simple reasoning, it can be seen that these rearrangements are accompanied by a rapid cluttering of the upper level by those containers that are waiting for final removal. The possibility of necessary additional movements to free the aisles at this level was only formally taken into account and was excluded from the calculations.

In order to clear the upper level, a more complex scheme with temporary lowering of containers was considered (see fig. 7). For this variant, calculations with random retrieval orders were performed.

A block with 4 stacks and 3 rows was considered. As a result, the difference in energy-costs between the worst and the best initial filling scheme was found. This difference amounted to about 30 %.

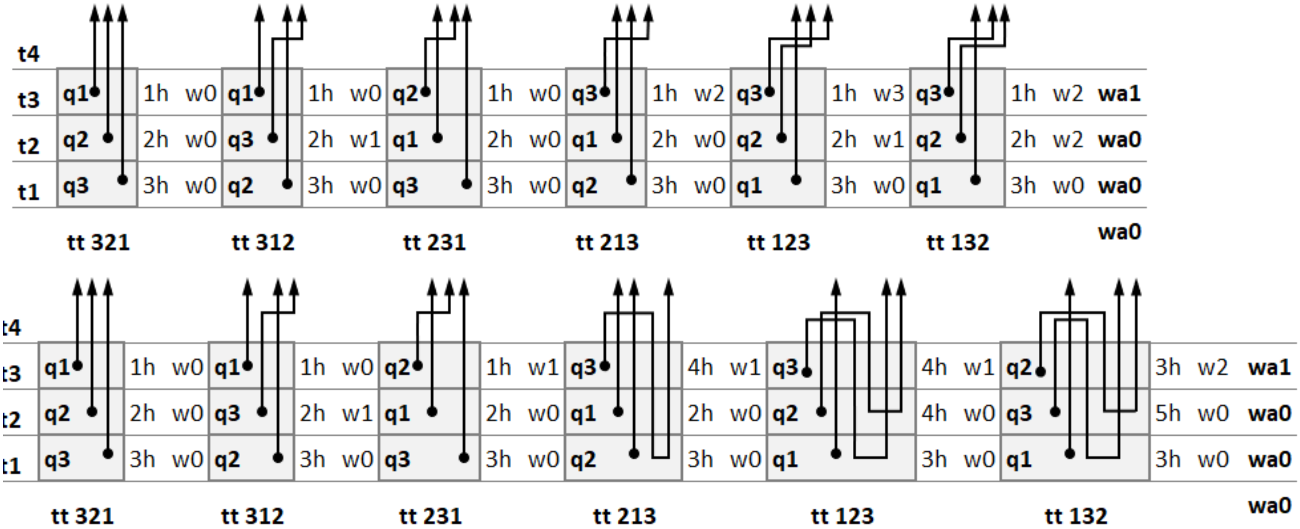


Fig. 7 – Container movement schemes in a stack with 3 tiers

The main issue became clear when the problem for a 4-level stack was considered (respectively, the number of possible combinations increased by a factor of 4). The cluttering of the upper levels was unacceptable and the total vertical displacements were too large. The scheme was found to be completely unsuitable. Nevertheless, the negative results led to several useful conclusions. In particular, the appropriateness of stack formation by stage. Also important was the confirmation that optimization is possible in principle.

The problem of optimizing the arrangement of containers in the transverse row of a stack.

The problems considered earlier have been studied by a number of authors, first of all, in the absence of a given ordering of the initial arrangement of containers. A somewhat opposite approach is also known, which consists in optimizing the initial arrangement of containers in each transverse row of the stack.

This task is of particular importance in the context of energy efficiency of forming/disassembling operations. The resulting scheme may seem paradoxical. For example, such a scheme was considered by Chen and Langevin [19] (see fig. 8) for the case of container export operations, where the sequence of filling the ship's holds may matter i.e. quality container ship loading involves placing heavier containers in the holds below and lighter containers on top. The specificity of such a task requires first of all to ensure correctness of ship loading, and reduction of energy consumption during stack operations is a secondary requirement, which is nevertheless taken into account.

9	8	7	6	5	4
8	7	6	5	4	3
7	6	5	4	3	2
6	5	4	3	2	1

Fig. 8 – Possibility to remove a container from the bottom row with transfer above and to the side of obstructing containers [19]

A 9-rank grading of containers by their weights was considered and a diagonal weight sorting filling was proposed for a 6x4 row scheme. Despite a pronounced undesirable shift of the overall center of gravity upwards, the scheme provides benefits, primarily due to the elimination of additional operations of rearrangements of containers.

In the following, a different scheme is considered, which allows for a higher degree of energy savings.

Scheme of cross row formation with sorting of containers by weights and by columns

The described scheme can be used for large stacks. It is simple and allows to set the sequence of both disassembly and assembly of the stack (in reverse order). When describing the scheme below, the disassembly sequence was considered, as this is the "traditional" variant. The basic rules are as follows.

All container movements during retrieval are sideways and downward only. The row is divided into a main zone and an additional zone. Containers in the main zone are sorted by weight independently for each column (heavy at the bottom). There may be no additional zone. Its purpose is to fill the empty space for a more complete utilization of the storage area.

The placement of containers in the additional zone is only to ensure unobstructed retrieval, without regard to weights.

The additional zone at the bottom is allocated to facilitate the removal of the lower, last containers in the columns.

Figure 9 shows 2 layouts for a cross row with a height of 6 containers. In diagram 1, the arrangement in the additional zone on the right side can be done in different ways, with increasing removal numbers from right to left and from top to bottom.

As an example, diagram 1b shows a variant of the row arrangement. In Scheme 2, extraction in the extra zone on the right can only be performed top-down. This is a significant limitation, but on the other hand, the overall center of mass of the containers in this zone is shifted downwards, which is a positive feature.

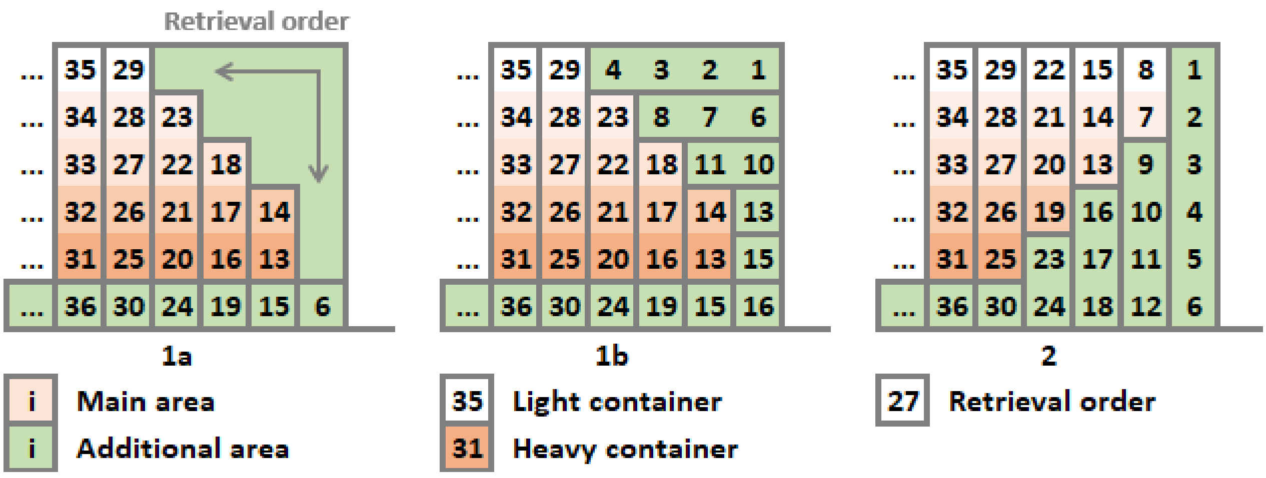


Fig. 9 – Dividing the row into areas with and without mass sorting

The disassembly procedure is shown in Fig. 10. For scheme 1, the additional zone is dismantled first. Then the columns are dismantled in such a way that all the containers except the lowest one are placed in 1 row horizontally on the area freed up by the dismantling of the previous column, i.e. with transposition. For scheme 2 the disassembly of the main and additional zones is combined. In this case, starting from the 4th column, the sequence of actions for schemes 1 and 2 have no differences.

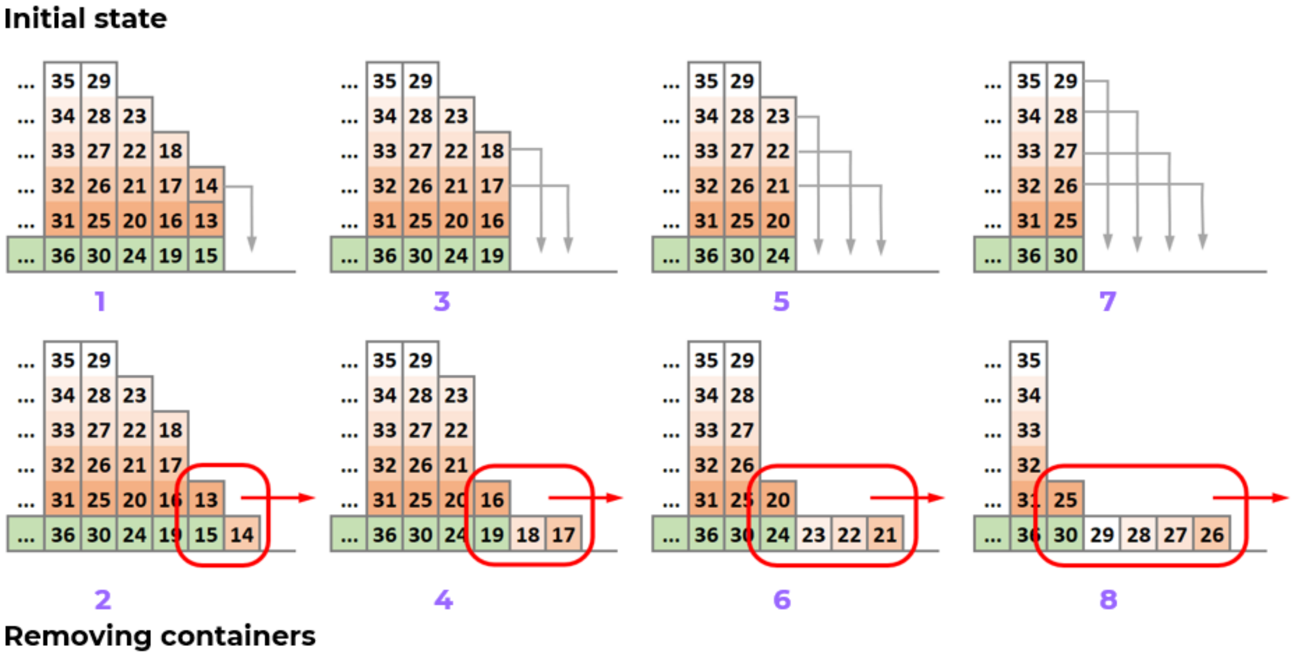


Fig. 10 – Fragments of the container disassembling sequence

The bottom additional zone may not exist. To do this, it is necessary to move the last container in the column above or next to the other containers (fig. 11).

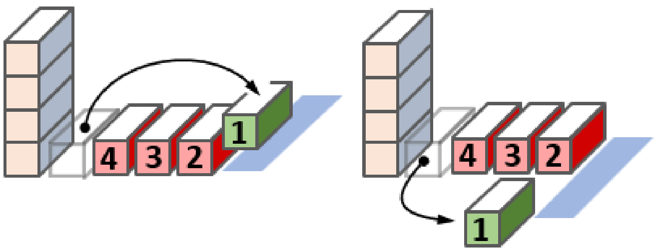


Fig. 11 – Possibility to remove a container from the bottom row with transfer above and to the side of obstructing containers

The difference of the energy problem is the accumulative nature of the optimized criterion, whereasin a well-developed time-minimizing problem it is important to eliminate the "bottle-neck"

Results and discussion.

The requirement to remove the container from blocked areas of the stack is not relevant in all cases. For example, it is not required for loading on ships and railroad platforms. Therefore, the considered problem has quite a certain area of applicability.

The difference of the energy problem is the accumulative nature of the optimized criterion, whereas in a well-developed time-minimizing problem it is important to eliminate the "bottle-neck" of the cargo flow intensity. These approaches are fundamentally different. When solving the energy problem, it is desirable to take into account losses when performing the largest number of operations, and cost estimation is most correct at the level of supplying power grids.

The application of a common model of yard RTG crane with AC power supply without regeneration was considered.

The main results were obtained by evaluating the energy consumption of the crane when performing different working movements with different loads. Due to the fact that the main consumption occurs when lifting the load, and the largest number of lifts is performed when forming the stack, it was found necessary to take into account the process of forming the stack along with its disassembly. However, such a task is complicated and its solution is beyond the scope of this study. We only note that the minimum cost of stack assembling will be provided at the lowest position of the center of gravity of all containers. In this case, however, the disassembly process will be extremely complicated. Therefore, optimization is required for the combined assembly-disassembly problem.

Thus, the specificity of the considered issue significantly affects the applicability of a particular technique. On the other hand, we have tried to use this specificity to simplify the disassembly process. We have considered a very simple stacking scheme and its corresponding sequence of removal from the stack without additional lifting. This scheme provides a sufficiently low center of gravity of the stack, which is beneficial during disassembly. The scheme also provides acceptable disassembly speed and energy consumption during forming.

The obtained result requires further numerical analysis. Without it the conclusions about the efficiency of the scheme are tentative. Such an analysis can be a comparative procedure, such as the one performed in [12].

A static problem has been considered, while there is often a need to replenish a stack at the same time as it is unloaded. It can be noted that such a need can be solved by replenishing fully vacated areas.

We have considered work movements with the highest possible speed. However, if necessary, the speed can be reduced. This can give a certain energy saving due to the dependence of the work on mass acceleration on the square of the velocity.

This scheme, as well as others, can be used for correct selection of new equipment. In particular, during idle (and also during working) horizontal movements operators often raise the spreader to the topmost position to avoid swaying. There are variants of technical solutions to this problem. A crane with the appropriate equipment can be more expensive and its purchase needs to be justified.

Assembling of the stack, if performed simultaneously with disassembling, in the simplest case can be performed on the vacated space, provided that disassembling is performed sequentially - along the transverse rows and from one end to the other.

The scheme is convenient for analyzing the efficiency of periodic crane moves for alternate unloading of containers in adjacent transverse rows. If this possibility is taken into account, the original arrangement plan in each row can be adjusted to a more favorable side. The relevant considerations are explained by an example. In Fig. 12, the numbers of containers in the extraction sequence are indicated by numbers. The 3 arrangements on the left show 2 columns in adjacent transverse rows, which are unloaded alternately. The containers in the right row are irrationally arranged because they have more weight, which cannot be corrected by sorting vertically. Conversely, the containers in the left row are light. The arrows show the different "castling" between the rows. It can be seen that as a result, the overall center of gravity of the 2 columns is significantly lower. At the same time, the retrieval order for both columns still provides only sideways and downward movement. Loading on a pair of consecutive trailers or, better still, on a Multi Trailer allows 2 containers to be removed from a column in any order. This, for example, eliminates the problem of removing the containers of the bottom extra row without having to carry them over or to the side of the interfering containers.

If the arrangement of containers in the additional zone is too irrational for an individual cross row, the additional zone can be abandoned, which does not affect the completeness of the stack as a whole too much.

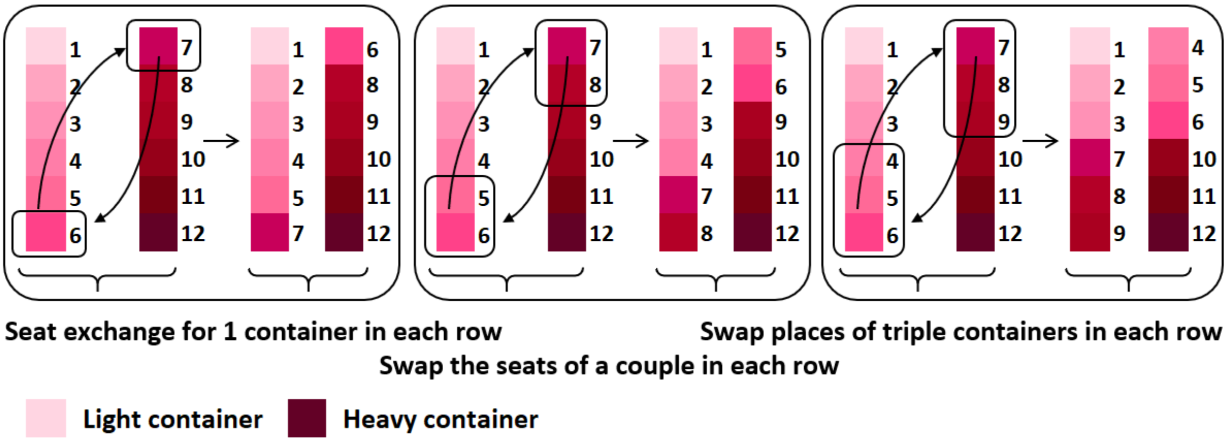


Fig. 12 – Container swap schemes in adjacent rows that provide a lower position of the overall center of gravity

Conclusion.

In this study, the energy consumption to perform the working movements of a container terminal yard crane has been calculated in a wide range of input data. The case of full electrification with grid powered without regeneration was considered.

Confirmation of the highest significance of load lifting was obtained. As a result, it was concluded that it is necessary to reduce the overall center of gravity of the stack. In this regard, attention is drawn to the importance of considering the energy costs not only during disassembling but also during assembling the stack. The lowest position of the center of gravity, however, is associated with the need to remove containers with multiple repositioning, which in turn requires additional significant energy consumption.

As a compromise, a simplified arrangement of the containers is proposed, which ensures unobstructed retrieval with only lateral and downward movements, satisfactory disassembly time and not too high energy consumption during loading containers to the stack.

The proposed scheme, despite its many advantages, is difficult to implement in practice because of the need for additional sorting zones. This feature is common for the problem of preliminary stack ordering. In any type of ordering it is necessary to organize the arrival of containers in a certain order. In order to achieve this, additional rearrangements are required at designated locations. The size of such places depends on the final configuration of the stack. Thus, provided that the number and height of lifts during sorting are minimized, to fill one transverse row with a height of n containers requires a sorting area having a length of n-1 lengths of one row. The above estimate is very approximate. Optimization calculations are needed in specific cases.

It can also be noted that any measures to reduce energy consumption are only possible if the requirements for operations at high speed and at maximum warehouse capacity are met. However, as energy costs rise, this approach will be gradually revised.

In particular cases, a partial implementation of the proposed scheme may be of practical interest, e.g., in some limited area of the bay. In further research it is intended to consider the combined assembling-disassembling problem and also the possibility of energy recovery to the grid.

References:

1. Steenken, D., Voß, S., Stahlbock, R.: Container terminal operation and operations research – a classification and literature review. OR Spectrum, vol. 26(1), 3–49 (2004). doi: 10.1007/s00291-003-0157-z.
2. Boxbay: Boxbay High Bay Storage. https://www.boxbay.com/boxbay-high-bay-storage, last accessed April 20, 2024
3. Konecranes: Automated High-Bay Container Storage. https://www.konecranes.com/port-equipment-services/container-handling-equipment/automated-high-bay-container-storage, last accessed April 20, 2024.
4. Logistics-manager: DP World Antwerp Gateway orders fleet of Automated Stacking Cranes from Konecranes. https://logistics-manager.com/dp-world-antwerp-gateway-orders-fleet-of-automated-stacking-cranes-from-konecranes/, last accessed April 20, 2024.

5. Forkliftaction: Gottwald Port Technology supplies stacker cranes for P&O. https://www.forkliftaction.com/news/gottwald-port-technology-supplies-stacker-cranes-for-po.aspx?n=2448, last accessed April 20, 2024.
6. BIV: B.C. court upholds $500K wages fine against port trucking companies. https://www.biv.com/news/economy-law-politics/bc-court-upholds-500k-wages-fine-against-port-trucking-companies-8273322, last accessed April 20, 2024.
7. Buiscar Cargo Solutions: Buiscar terminal trailers. https://www.buiscar.com/products/terminal-trailers/, last accessed April 20, 2024.
8. Wu, K. C., Ting, C. J.: A beam search algorithm for minimizing reshuffle operations at container yards. In: Proceedings of the international conference on logistics and maritime systems, Busan, Korea, September 15-17 2010.
9. Konecrains: Konecranes RTG: from the creator of the modern RTG. https://www.konecranes.com/sites/default/files/2021-06/RTG_typical_tech_specs_0.pdf/, last accessed April 20, 2024.
10. Cobo, P.T.: Optimization of yard operations in container terminals from an energy efficiency approach. PhD Thesis, Universitat Politècnica de Catalunya (2016).
11. Hussein M., Petering M.E.H.: Genetic algorithm-based simulation optimization of stacking algorithms for yard cranes to reduce fuel consumption at seaport container transshipment terminals. 2012 IEEE Congress on Evolutionary Computation, CEC 2012 1, 10–15 (2012). doi: 10.1109/CEC.2012.6256471.
12. Durasevic, M., Dumic, M., Coric, R., Gil Gala, F.J.: Automated design of relocation rules for minimising energy consumption in the container relocation problem. In Sara Silva, Luís Paquete, editors, Companion Proceedings of the Conference on Genetic and Evolutionary Computation, GECCO 2023, Companion Volume, Lisbon, Portugal, July 15-19, 2023, pp. 523-526, ACM (2023).
13. Lu, C., Zeng, B., Liu, S.: A study on the block relocation problem: Lower bound derivations and strong formulations. IEEE Trans. Autom. Sci. Eng. 1–25 (2020). doi: 10.1109/TASE.2020.2979868.
14. Коваленко, В.О., Турчин, О.В., Алєксєєв, В.І., Стрижак, В.В., Поляков О.А. Підвищення ефективності операцій з контейнерами в штабелях контейнерних портових терміналів. Матеріали Інформаційні технології: наука, техніка, технологія, освіта, здоров'я: тези доповідей XXXII міжнародної науково-практичної конференції MicroCAD-2024, 22-25 травня 2024 р. / за ред. проф. Сокола Є.І. Харків: НТУ «ХПІ».
15. Lin, K., Meier, C., Zaahir, J. N.: Environmental Defense Fund (EDF) Logistics Project: The Greening of Rubber-Tired Gantry Cranes in Ports In partnership with the Port of Oakland. 15.915 Laboratory for Sustainable Business (2014).
16. Scheffler, M.: Grundlagen der Fördertechnik - Elemente und Triebwerke (Fördertechnik und Baumaschinen). Springer Fachmedien Wiesbaden (1994).
17. Verschoof, J.: Cranes – Design, Practice and Maintenance 2nd Edition. Professional Engineering Publishing Limited, London (2002).
18. Conductix wampfler. RTG/RMG Container Crane. https://www.conductix.us/en/applications/rtgrmg-container-crane, last accessed September 20, 2024.
19. Chen, L., Langevin, A.: Determining the storage location for outbound containers in a maritime terminal. Industrial Engineering and Engineering Management (IEEM 2009). Proceedings of the IEEE International Conference on. 8-11 Dec. 2009, Hong Kong. DOI:10.1109/IEEM.2009.5373283

References (transliterated):

1. Steenken, D., Voß, S., Stahlbock, R.: Container terminal operation and operations research – a classification and literature review. OR Spectrum, vol. 26(1), 3–49 (2004). doi: 10.1007/s00291-003-0157-z.
2. Boxbay: Boxbay High Bay Storage. https://www.boxbay.com/boxbay-high-bay-storage, last accessed April 20, 2024
3. Konecranes: Automated High-Bay Container Storage. https://www.konecranes.com/port-equipment-services/container-handling-equipment/automated-high-bay-container-storage, last accessed April 20, 2024.
4. Logistics-manager: DP World Antwerp Gateway orders fleet of Automated Stacking Cranes from Konecranes. https://logistics-manager.com/dp-world-antwerp-gateway-orders-fleet-of-automated-stacking-cranes-from-konecranes/, last accessed April 20, 2024.

5. Forkliftaction: Gottwald Port Technology supplies stacker cranes for P&O. https://www.forkliftaction.com/news/gottwald-port-technology-supplies-stacker-cranes-for-po.aspx?n=2448, last accessed April 20, 2024.
6. BIV: B.C. court upholds $500K wages fine against port trucking companies. https://www.biv.com/news/economy-law-politics/bc-court-upholds-500k-wages-fine-against-port-trucking-companies-8273322, last accessed April 20, 2024.
7. Buiscar Cargo Solutions: Buiscar terminal trailers. https://www.buiscar.com/products/terminal-trailers/, last accessed April 20, 2024.
8. Wu, K. C., Ting, C. J.: A beam search algorithm for minimizing reshuffle operations at container yards. In: Proceedings of the international conference on logistics and maritime systems, Busan, Korea, September 15-17 2010.

9. Konecrains: Konecranes RTG: from the creator of the modern RTG. https://www.konecranes.com/sites/default/files/2021-06/RTG_typical_tech_specs_0.pdf/, last accessed April 20, 2024.
10. Cobo, P.T.: Optimization of yard operations in container terminals from an energy efficiency approach. PhD Thesis, Universitat Politècnica de Catalunya (2016).
11. Hussein M., Petering M.E.H.: Genetic algorithm-based simulation optimization of stacking algorithms for yard cranes to reduce fuel consumption at seaport container transshipment terminals. 2012 IEEE Congress on Evolutionary Computation, CEC 2012 1, 10–15 (2012). doi: 10.1109/CEC.2012.6256471.
12. Durasevic, M., Dumic, M., Coric, R., Gil Gala, F.J.: Automated design of relocation rules for minimising energy consumption in the container relocation problem. In Sara Silva, Luís Paquete, editors, Companion Proceedings of the Conference on Genetic and Evolutionary Computation, GECCO 2023, Companion Volume, Lisbon, Portugal, July 15-19, 2023, pp. 523-526, ACM (2023).
13. Lu, C., Zeng, B., Liu, S.: A study on the block relocation problem: Lower bound derivations and strong formulations. IEEE Trans. Autom. Sci. Eng. 1–25 (2020). doi: 10.1109/TASE.2020.2979868.
14. Kovalenko, V., Turchyn, O., Alieksieiev, V., Stryzhak, V., Poliakov O.: Pidvyshchennia efektyvnosti operatsii z konteineramy v shtabeliakh konteinernykh portovykh terminaliv. Materialy Informatsiini tekhnolohii: nauka, tekhnika, tekhnolohiia, osvita, zdorovia: tezy dopovidei XXXII mizhnarodnoi naukovo-praktychnoi konferentsii MicroCAD-2024, 22-25 travnia 2024 r. / za red. prof. Sokola Ye.I. Kharkiv: NTU «KhPI».
15. Lin, K., Meier, C., Zaahir, J. N.: Environmental Defense Fund (EDF) Logistics Project: The Greening of Rubber-Tired Gantry Cranes in Ports In partnership with the Port of Oakland. 15.915 Laboratory for Sustainable Business (2014).
16. Scheffler, M.: Grundlagen der Fördertechnik - Elemente und Triebwerke (Fördertechnik und Baumaschinen). Springer Fachmedien Wiesbaden (1994).
17. Verschoof, J.: Cranes – Design, Practice and Maintenance 2nd Edition. Professional Engineering Publishing Limited, London (2002).
18. Conductix wampfler. RTG/RMG Container Crane. https://www.conductix.us/en/applications/rtgrmg-container-crane, last accessed September 20, 2024.
19. Chen, L., Langevin, A.: Determining the storage location for outbound containers in a maritime terminal. Industrial Engineering and Engineering Management (IEEM 2009). Proceedings of the IEEE International Conference on. 8-11 Dec. 2009, Hong Kong. DOI:10.1109/IEEM.2009.5373283

Надійшла (received) 01.10.2024 р.

Відомості про авторів / About the Authors

Коваленко Валентин Олександрович (Kovalenko Valentyn) – кандидат технічних наук, професор, Національний технічний університет «Харківський політехнічний інститут», завідувач кафедри підйомно-транспортних машини і обладнання; м. Харків, Україна; ORCID: https://orcid.org/0000-0001-9161-198X; e-mail: valentyn.kovalenko@khpi.edu.ua.

Турчин Ольга Володимирівна (Turchyn Olha) – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри підйомно-транспортних машин і обладнання; м. Харків, Україна; ORCID: https://orcid.org/0000-0002-9153-3704; e-mail: olha.turchyn@khpi.edu.ua.

Алєксєєв Володимир Ігорович (Alieksieiev Volodymyr) – Гамбурзький технічний університет, науковий співробітник інституту виробничого менеджменту та технологій; м. Гамбург, Німеччина; ORCID: https://orcid.org/0000-0003-0792-3740; e-mail: volodymyr.alieksieiev@tuhh.de

Стрижак Всеволод Вікторович **(*Stryzhak Vsevolod*)** – кандидат технічних наук, доцент, Національний технічний університет «Харківський політехнічний інститут», доцент кафедри підйомно-транспортних машин і обладнання; м. Харків, Україна; ORCID: https://orcid.org/0000-0003-3032-6004; e-mail: vsevolod.stryzhak@khpi.edu.ua.

Стрелков Максим Борисович (Strelkov Maksym) – Національний технічний університет «Харківський політехнічний інститут», аспірант кафедри підйомно-транспортних машин і обладнання; м. Харків, Україна; e-mail: maksym.strelkov@mit.khpi.edu.ua.

Поляков Олексій Андрійович (Poliakov Oleksii) – Національний технічний університет «Харківський політехнічний інститут», студент кафедри підйомно-транспортних машин і обладнання; м. Харків, Україна; ORCID: https://orcid.org/0009-0001-4436-3001; polyakovalx14@gmail.com.