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New Approach In Models for Managing the Vessel Unloading Process

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ABSTRACT: New way of formalizing hybrid systems in models for managing the process of vessel unloading is caused by the significant increase in container transportation around the world over the past decade. The growth of container traffic is the main reason for the constant modernization of port container terminals and the improvement of cargo unloading technology is most promising when using those methods, that allow obtaining maximum results in terms of cargo processing speed. This problem is the subject of an article in which an analytical review of container handling technologies existing in world ports is carried out, their key performance indicators are formulated and it is shown how the use of a centralized hybrid control system based on the dynamics of discrete events can lead to increased profitability of the port. Developed concept of a hybrid control system makes possible to consider such features of the vessels unload process that have not been considered until now.

1 INTRODUCTION

In recent decades, there has been a significant increase in container transportation worldwide. This fact is objective, since in addition to the growth of production in the world industry, the number of vessels is also rapidly increasing. A good confirmation is statistical data on the growth of the sea vessels quantity. According to [10] during last 15 years a number of sea vessels on the planet fleet enlarged about 53% with growing of their gross by 47%.

By using a container the cargo can be stored in a standard steel box during transport without opening. Standardization leads to flexibility, low transport costs and rapid transshipment, particularly when the cargo is moved over long distances. Thanks to these advantages, containers are widely used in a global freight transport, which consists of an extremely large and complex structure of distribution systems and business activity. In these systems, a container is typically intermodally transported from an origin to a destination, where two or more transport units (e.g. ships, barges, trains and trucks) are used in sequence. Manufacturers, forwarders, shipping companies, terminal operators and customers are involved in the process of container cargo handling. All of them form a large supply chain [10] and this technological chain is constantly changing and mostly in almost all seaports on the planet it is caused by varying operational and safety standards.

Port terminals, as transport hubs, play an important role in the container transport network. They play main role in the vessel's interaction with various types of transport. Transshipment of containers from one type of transport to another is carried out at intermodal container terminals.

An analysis of the current level of theoretical statements and methodological principles related to intermodal transportation, in particular, optimization of the management of automated processes of container ships cargo operations, shows that they have remained understudied. The same applies to the substantiation of trends in the use of automated technical equipment, as well as the analysis of conceptual approaches to improving the efficiency of cargo handling of container ships.

It should be noted that many problems from the list of port operation risks are still out of port's control. Correct analysis of connection between these risks and the reasons that caused them can lead to creation of radically new models of managing the process of ship unloading.

2 MATERIALS AND METHODS

2.1 *Modern trends in the use of container ship processing technologies*

2.1.1 *Trends in the development of automation of vessel's cargo handling processes*

The limitation of the existing theoretical and methodological developments on the above-mentioned problems increases the relevance and significance of conducting new research in the field of forming methods for optimizing the management of processes of container ships cargo operations.

A very important question is the generalization of theoretical knowledge about container ships cargo handling processes and the development of practical recommendations for their application in the management of automated technologies. Practically all production problems in this case can be reduced to the best level of solution. The subsequent implementation of such a solution can be used in the work of any port if there would be realized the following operations: to justify the development trends of the automation of cargo operations processes; to analyze new concepts for increasing the efficiency of cargo handling; to determine the methodological basis for key performance indicators evaluating; develop proposals for optimal management of container ships cargo handling processes; to evaluate general indicators of the investing feasibility in the automation of cargo terminals.

In fact, it can be stated that new theoretical and methodological foundations of managing the automated processes of container ships cargo operations can give the highest indicators of the profitability of port operations. During research works, it was stated that the main and, at the same time, the most promising trends in the development of the work of port terminals consist in the realization of the following directions:

- development of methodological bases for evaluating the efficiency of processes of container ships cargo operations at automated terminals using analytical methods and considering the dynamics of continuous time and discrete events;
- creation of a new principle of optimizing the management of cargo handling processes of container ships, expressed in the ratio between the time of cargo operations and the energy efficiency of automated equipment;
- the development of a technological system that uses new criteria for evaluating indicators of improving the efficiency of ship cargo handling in the port;
- creation of new methods for assessing the feasibility of investing in the automation of cargo terminals.

2.1.2 *Influence of automation on the quality of port operations*

During the research, there was used classification of automatic equipment, which was proposed in [12]. In accordance with it, processing a vessel in the port involves the use of only three components. The first refers to those technological operations that occur on a vessel in the port while it is berthed. The second refers to those technological operations that are associated with storing cargo at the port berth. The third relates to the transport of cargo from the berth or to local areas of the port or directly outside the port.

In a port, when carrying out cargo operations with a ship that is berthed, three types of automated equipment are usually used: remote quay cranes (QC), automated cargo vehicles (AGV) and stacker cranes (ASC). This equipment is energy-intensive and an increase in overload abilities will always lead to a significant increase in the energy consumed. However, in accordance with the data from [13], the fact of increasing energy consumption is an incentive for the creation of new types of more autonomous equipment.

Nowadays, more and more new technical developments are appearing at port terminals. A good example in this case is a GPS-based AGV. This type of AGV ensures free behavior and significantly speeds up travel along the standard path, which is fixed or governed using various methods (wires, lasers, AI optical vision, etc.), but it is necessary to note that freedom in AGV's behavior enlarges difficulties for managing terminal operations. From one side, preventing of two AGVs collision should be considered from the safety point of view. On the other hand, AGV interacts with other types of machines that are used during shipboard operations (loading or unloading).

Analysis of statistical data allows to conclude that work in the port was and is extremely dangerous. According to Pacific Maritime Association (PMA) statistics, the injury rate by 1960 was three to four injuries per full-time employee each year. This grim picture has changed dramatically as continuity-enhancing operations have been abandoned in favor of containerization. By the end of 1970, the number of injured people was approximately 15 per 100 full-time workers, which is 95% lower than the level that existed before containerization [5].

In the analytical article [14], the trends of increasing the level of security after containerization are revealed in detail and the possibilities of obtaining additional advantages in the field of security by increasing automation and new algorithms for managing ship cargo handling systems are studied.

Work [6] investigated the cases of injuries in the ports of the West Coast of the United States (United States West Coast, USWC) and predicted that the frequency of injuries will steadily decrease over time. Thus, since 1997, the frequency has decreased to 1 annual injury per 10 full-time workers (less than one-thirtieth of the frequency in 1950). This was primarily due to the improvement of the quality of safety equipment and training, which allows consider past accidents and change the behavior accordingly. In subsequent years, the decrease in the number of injuries is due to the use of more automated equipment.

Statistics from the last two years continue to indicate a very big importance of security issues within the area of port or port terminals. In 2022, 50% of maritime accidents took place in ports and port terminals and as one can see in Figure 1 [3] main part of these accidents answers to: berth, port using facilities, during port and harbor transit. RightShip data [3] shows that 818 accidents in 2022 has happened in ports.

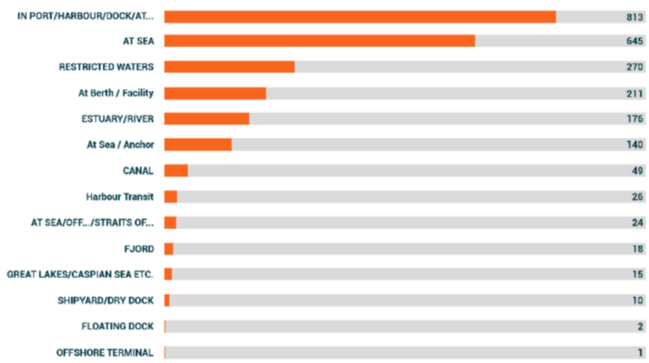


Figure 1. Number of maritime incidents by vessel location in 2022 [3]

From our point of view, the use of new cargo handling management systems in seaports will lead to an even greater reduction in injury rates. In general, this will happen due to the use of non-standard solutions when using control algorithms, since hybrid systems allow to consider such features of the cargo unloading process from a ship, which have not been considered until now. One of these indicators can be the velocity of movement of all system elements depending on such external factors as weather conditions, current time of the day, number of workers in the dangerous zone, etc.

2.1.3 *Analysis of modern cargo handling systems and technical support of automated container terminals*

The standard list of works, which is performed at the berth during vessel's cargo unloading, consists in the use of quay cranes (QC) at the first stage. At the second stage the cargo is moved to the cargo area or warehouse with the help of vehicles. These types of transport are mainly: trucks (YT), container loaders (SC) and automated guided vehicles (AGV). During inland operations, containers are delivered to the gate by road trucks and all their documents and damage are checked.

Container cargo handling systems in the port terminal are recognized as standard and divided into two types [3]. The first type of system uses indirect transmission and involves two different types of lifting equipment: trucks and conveyors. Appropriate warehouse cranes (Yard Crane, YC) are used to handle containers in the stacking area. The second type of system uses a tractor or SC. When SCs are used as conveyors, the stacking height is lower than in the first type of system. Since in almost all ports on the planet the need for storage is high and storage space is very often not enough, and the first type of systems is usually used.

A very high-quality example of how the automation of cargo equipment can significantly increase the operational speed of port container terminals is Figure 2, which shows an ordinary quay crane [7]. Its automation makes it possible to increase the number of containers per lift when other things being equal.

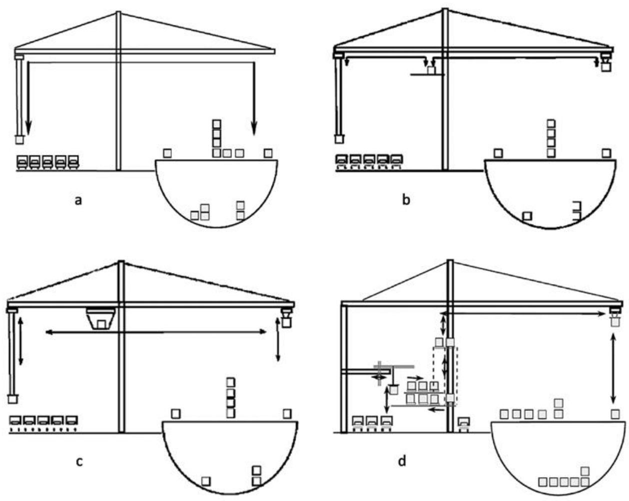


Figure 2. Automatization of QC [7].

Figure 2-a shows a standard QC design with one cart. In fig. 2-b QC already uses two trolleys: the first moves over the berth and the second moves over the vessel on the same track. The whole process can be divided into two cycles: transferring the container to and from the platform. Figure 2-c shows the SupertainerTM developed by Paceco Corporation and in its design it has two carts with a platform for moving containers from one cart to another. As a result, the QC cycle is divided into three segments, which further reduces the time of each individual cycle. The conceptual project in which two lifts are installed between the carts is shown in fig. 2-d. They are responsible for the vertical movement of containers. There are also two small conveyors that move containers on different levels. It is expected that this crane can increase the loading capacity to 94 containers per hour, which is a significant increase in productivity compared to the productivity achieved by traditional QCs, which is 38 containers per hour [7].

A review of the transmission system shows that the most popular transport equipment is a conveyor consisting of a truck and a frame. The automated version of trucks is the Automated Guided Vehicle (AGV). One of the disadvantages of using trucks or

AGVs is the possibility that a crane or transporter may have to wait an arrival of another type of equipment to transfer the container. Another type of transporter is a container handler (SC). They can lift containers directly from the berth, eliminating the need for a transfer operation.

When using an AGV to transport containers, the operation of the crane can be separated from the operation of the conveyor. This can be done by using buffer stations that eliminate the need to transfer containers between cranes and vehicles. Such stations are racks - steel platforms that are separated from the AGV and on which containers are located. With such a technological solution, QC or AGV can leave containers on the rack even before other equipment reaches the transfer position.

In addition to improving the equipment of transporters in almost all modern ports, many port authorities and operational teams are making significant efforts to improve the commercial sense to attract vessels in the field of operational efficiency optimization. This is mainly implemented in practice by using high operational standards, improving algorithms and rules for the compatible operation of equipment, reducing inherent risks. For automated conveyors, methods of effective dispatching, routing, planning and traffic control are constantly being developed and applied in practice.

Simultaneously with the need for storage space, the height of the stacks also increases. In the early days of container terminals, the stack height was 1-3 tiers. When SC spread, the stack height was 2-3 tiers, and after YS spread, the stack height was 4-6 tiers [17]. As the stack grows, more attention should be paid to reprocessing operations. Various algorithms and rules have been developed to minimize these operations.

An analysis of the transshipment capacities of all ports on the planet allows us to draw an unequivocal conclusion - the tendency to their growth will be observed until the size of transport vessels increases.

2.1.4 *Analysis of technologies for increasing the efficiency of the process of container ships cargo handling*

The efficiency of the process of container ships cargo handling can be evaluated by using a set of indicators that have specific numerical ranges. They should change constantly to a greater extent and, depending on the type of equipment, which is used at the terminal, can be divided into three categories:

– for cranes: cycle time of processing one container; ability for multi lifting; crane deployment density;
– for transporters: time necessary to transport one container; carrying capacity;
– for warehousing equipment: maximal density of containers storage with the maximum permissible amount of overloading; number of cranes set to increase throughput with low interference.

In addition to these basic criteria, it is possible to use additional criteria to evaluate the efficiency of container ship cargo handling process. They should be considered when developing new concepts and the main ones are: flexibility, cost, environmental protection, technological feasibility, reliability.

Regarding flexibility, it should be considered that cargo handling system at the terminal should be applied with minor changes, even if the container flow pattern is different or the logistics environment changes. Once the control system is in place, it should be easily adaptable to ever-changing situation at the container terminal. Main characteristics of flexibility are the probability of application to different situations with the smallest modifications and the rate of adaptation to a changing situation.

Regarding the cost, there should be considered such numerical results as: a decrease in the amount of investment and a decrease in the cost of operations. It should be considered that the cost indicator depicts not only the cost of updating the technology itself, which is used at the terminal in the port, but also the cost of its operation in the feature.

Estimating the cost of environmental protection requires the use of volumes: total energy consumption and CO2 emissions.

Reliability indicators are mainly based on the assessment of the possibility of maintenance in the future and the recovery time to the working state during technological failures or accidents [15].

Many conceptual systems are used to improve the efficiency of container ships cargo handling process. The most effective include: Linear Motor Conveyance System (LMCS), Automated Storage and Retrieval Systems (AS/RS), Overhead Grid Rail (GRAIL), SPEEDPORT, SuperDock, ZPMC automated system, Teustack [7, 9, 11].

The unique features of LMCS are that the platform on which containers are stacked is used as a conveyor and can move along the track on a fixed trajectory with high positioning accuracy and high reliability. LMCS is an environmentally friendly system because it uses electricity instead of organic diesel fuel, which is the main energy source for trucks and most AGVs. The main disadvantage of LMCS is the high investment cost for initial construction. LMCS is limited also in the number of routes for platforms and this means that its conveyor routing flexibility is relatively low in comparison to truck-based or AGV-based systems.

Two main components of an AS/RS are Storage and Retrieval Machine (SRM) and storage racks. AS/RS has the advantages of providing high-density storage capacity, high throughput, and random access to the target container without overloading operations. It possible to create this system on a small spot of port territory and then easily add storage capacity by increasing the number of tiers. This is useful when space is limited and expensive.

Main disadvantage of SRM is high cost of construction and possibility of blocking in local space (at the entrance at the lowest level of each aisle there is an AS/RS station, which is located at one end) of all further operations in case of SRM failure.

GRAIL uses electric shuttles as main equipment elements, which are used for storage on the territory of the terminal and for containers delivery between the storage place and the wharf. They can move between suspended tracks when moving over stacks and transporting containers. This movement is ensured by the operation of switches and can take place directly between the pier and the railway station. The connection points between QC and shuttles are an advanced automated platform under QC, where the QC operation and shuttle management are separated. QCs pick up or place containers without attending to the entrance to the shuttle, and they in turn drop off or pick up containers without waiting for QC arrival. This operational algorithm reduces equipment waiting time.

Specificity of GRAIL's operation is that the plane of movement for the shuttles is completely in the air space. This makes it possible to save on redundant aisles and avoid obstacles with container stacks on the ground or with the trajectory of trucks with drivers.

Main disadvantage of GRAIL is a complex management system and high investment costs. This system is an attractive solution for locations where high urgent productivity is required but land for container storage is limited and expensive.

The Speedport system is actually a modernized analogue of the GRAIL system, as its track is extended above the ship's hull for the possibility of its operation. The main equipment is a spider, which performs dual functions - a truck and a shuttle (which is similar to the GRAIL shuttle). Each spider is self-propelled and moves along a network of aerial beams and ground tracks.

Speedport can reduce the time necessary to transfer cargo from cranes to vehicles in a system that uses traditional QC and YC with spiders. In this case, they can perform the functions of both cranes and trucks. The number of spiders that can work with one ship is large and this contributes to a significant increase in the overload capacity.

Disadvantage of Speedport is a very high cost of building the structure and the spiders themselves. Such a system has technical problems also. In most cases, they are related to the lack of flexibility when working with vessels of different sizes.

The SuperDock concept currently remains at the stage of theoretical development, since the initial investment costs for its implementation amount to billions of US dollars. It was developed out of the need for economically and environmentally beneficial container terminals in North American ports.

Operation of SuperDock is based on the use of the rail conveyor and universal stacking systems with a long dock that uses many QCs. On the other hand, SuperDock has a railway for trains. The use of Superdock system should reduce air pollution and noise.

In the ZPMC automated system, flat cars run on rails on two levels: an overhead track installed parallel to the QC track, and another laid on the ground in a direction perpendicular to the embankment. If necessary, more tiers can be added to the upper track. After the QC places the container on the flatbed car, it moves to a preset position to transport the container to the Rail-Mounted Gantry (RMG). At the beginning each RMG lifts the container, changing its spatial orientation by 90 degrees. The RMG container is then reloaded onto the lower AGV and the container is transported to the next automated RMG at the storage location.

Main advantages of ZPMC are: simplification of control over vehicles compared to the AGV system; increased reliability of the system and ease of support compared to traditional automatic container terminals; environmentally friendly system because it uses only electrical energy sources.

Main problems of ZPMC are the great complexity of planning the synchronous movement of all relevant equipment; high construction costs; lack of high operational flexibility in routing the movement of flatbed cars.

The latest Teustack system is the most promising and high-quality [4, 16]. This system is designed for transportation and storage of all types of containers: standard 20-foot and 40-foot containers, refrigerated containers, containers of increased capacity. In Teustack, as shown in Figure 3-a, after the moment when containers are unloaded from the vessel, cranes move them to specially designated receiving devices. After that, platforms with containers are moved to the first available storage space and come back to get new containers. Inside the terminal, as shown in Figure 3-b, there are shuttles. They are similar to rotary and distribution platforms and provide horizontal movement of containers on each floor.

Vertical movements in the system are provided by lifting cranes distributed along the aisles. After reaching the required level, containers are picked up by shuttles and transported to the final destination. All movements are performed simultaneously on different levels. This allows the system to control horizontal and vertical movements separately. Containers stored in the terminal are freely accessible and can be removed at any time without additional movements. Vessel loading operations are carried out similarly. Eight tiers allow storage of 6.4 thousand TEU on 25000 sqr. m. At a normal terminal, 100,000 sqr. m is needed for storage of 6.4 thousand TEU, which is 4 times more. Compared to standard ship cargo handling systems, Teustack has 70% more productivity, and also provides a sufficient level of safety and reliability.

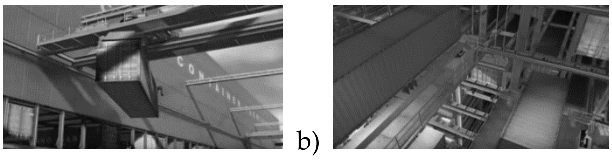
a)  b)

Figure 3. Teustack. a - mooring crane transports container to the Teustack platform; b - internal storage system

2.2 *Technical support and equipment operational characteristics of the biggest automated container terminals*

During the research, as automated terminals were considered those terminals where at least one type of equipment during its full operational cycle for containers handling works without direct human interaction. In most cases of container terminals discussed below, operators are not physically involved in the operation of the cranes, although sometimes they may be present in the cabins of the equipment. Modern equipment of such container terminals includes the following list: Automated Stacking Crane; Rail Mounted Gantry; Rubber Tired Gantry; Autostrad [8].

Automated Stacking Crane lift and transfer containers one by one to their destination in the limits of row. They are the current global standard for automated container terminals and perform most of the operating cycle autonomously without any interaction with operators. If necessary, they can be remotely controlled. Containers are delivered to them by automatic carriers or other types of transport - automated vehicles, container loaders, or human-operated vehicles.

Rail Mounted Gantry can work parallel and perpendicular to the wharf. The specific position of RMG for containers processing is determined by the density of their location. RMGs are used in many terminals around the world, especially in Asia. They are usually served by human-operated vehicles.

Rubber Tired Gantry are usually manually operated by operators in cabs and serviced by vehicles with drivers. The exception is Tobishima Container Terminal, Nagoya, Japan. This terminal uses unmanned RTGs and is serviced by automated guided vehicles.

Autostrads require a lot of space to allow movement and maneuverability. They do not have a high stacking height because container loaders have height restrictions. For this reason, the operation of the Autostrad results in a very low density of containers at the berth.

In the world most of the automated terminals, that are under development, focus on the use of ASC. This type of equipment is well compatible with various types of automated transport [1].

Provision of automated equipment for 6 terminals in Europe is given in Tables 1 and 2 [6]. Their analysis shows that a stacking height of 6 tiers has become the standard for automated cranes. Side-by-side ASCs range in length from 36 to 59 total container spaces (770 to 1,260 feet). Despite the fact that these restrictions are not strict, in a short row of containers, ASC is poorly implemented due to the high cost of the equipment itself, and in a long row, the processing time of containers increases significantly. The port terminals, with the exception of the two in Hamburg, use two identical ASCs on the same set of tracks.

The automated container handlers at both Hamburg terminals (Altenwerder and Burchardkai) have unique designs compared to other facilities around the world. They use two different pairs of tracks for the ASC, allowing the smaller loaders to pass under the taller ones. Burchardkai Container Terminal also has three ASCs, each with two smaller ASCs, although this reduces the stacking height to 4 tiers, while all other terminals with ASCs can stack up to 5 tiers.

Most modern terminals with ASC lay out containers perpendicular to the berth. However, it is increasingly possible to observe terminals where rows of containers are arranged in parallel. The width of the rows usually varies between 8 and 10 containers, with the exception of 12 rows of containers at the CTA and CTB terminals in Hamburg.

Main properties of automated equipment for largest six terminals in Europe formulated in Tables 1 and 2.

2.3 *Key Performance Indicators*

In container terminals, performance can be evaluated using a very large number of different indicators and therefore it is always necessary to determine the main ones - key performance indicators. The most important indicator of the terminal efficiency is the vessel’s service time. This indicator is connected with other performance indicators that directly relate to the terminal's transport processes. The main key performance indicators are:

Table 1. Main technical characteristics of container terminal equipment

Main properties	Name of ports and terminals					
	Hamburg CTA	Rotterdam Euromax	Antwerp DPW	Algeciras TTI	Hamburg CTB	Norfolk APMT
Height of ASC, TEU	4/5	5	5	5	4/5	5
Width ASC, TEU	10/12	10	9	8	10/12	8
Number of ASCs, pcs.	52	58	14	32	15	30
Type of motor vehicle	AGV	AGV	SC	Shuttle	SC	Shuttle
Length of the ASC, TGS row	37	36	41	45	45	59
General field ASC, TGS	9620	10440	7545	5760	17000	7080
Stack height, tiers	4	5	3	5	3	5
The highest use of the stack, %	75	75	75	75	75	75
Maximum stacking height in tiers	3.0	3.8	2.3	3.8	2.1	3.8
Total capacity, TEU	28860	39150	17129	21600	35700	26550
Total terminal size, acres.	247	208	138	74	346	234
Expected annual throughput, million TEU	2,3	1,8	1,0	1,0	2,9	0,7
Length of coastline, feet.	4590	4920	6100	3940	9350	3025
Number of port cranes, pcs.	15	16	9	8	25	6
Type of the port crane	Double cart, automat.	Double cart, automat.	One cart	One cart	Double cart, automat.	One cart

Table 2. Estimated operational parameters of container terminals

Operational parameters	Name of ports and terminals					
	Hamburg CTA	Rotterdam Euromax	Antwerp DPW	Algeciras TTI	Hamburg CTB	Norfolk APMT
TGS on 1 acre	39	50	55	78	49	30
Static capacity of 1 acre	117	189	124	291	103	113
Berth length for 1 crane, m	306	308	678	493	374	504
Annual number of containers per 1 acre	9300	8700	7300	13500	8400	3000
Annual number of lifts per 1 crane	87000	63000	67000	75000	68000	67000
Annual number of lifts per foot of pier	280	200	100	150	180	130
Waiting time, days	4,6	7,9	6,3	7,9	4,5	13,8

1. Service time, hours It is defined as the time during which the vessel is at the berth for the purpose of loading or unloading. This indicator is defined as the most important factor in the total transport cost of containers because it directly reflects the productivity of terminal operators.
2. Time of works completion, hours. This indicator corresponds to the time of cargo operations completion using that part of the terminal equipment that is directly related to the time of ship service.
3. Energy consumption, kWh. This indicator corresponds to the total electricity that was used to transport containers between ship and storage location or vice versa.
4. Time for calculations, sec. This indicator corresponds to the time period that was spent on solving a specific optimization problem related to container processing.
5. Average distance of AGV movement, m. This indicator corresponds to the average distance AGV moves between the point of transfer at the wharf and the point of stacking in the terminal.
6. Relative distance of AGV, m. This indicator corresponds to the distance between the two AGVs used for transporting containers.
7. Operation of QC, %;
8. Operation of AGV, %;
9. Operation of ASC, %.

The last three indicators mean the average value of the percentage of time during which the respective equipment, i.e. QC, AGV and ASC, was used during the vessel's unloading or loading.

3 FORMALIZATION OF HYBRID SYSTEMS IN MANAGEMENT MODELS WITH CONSIDERING OF KEY PERFORMANCE INDICATORS

3.1 *Dynamics of discrete events*

In quayside operations of automated container terminals, QC, AGV and ASC work together to load or unload a vessel. When formalizing hybrid systems in terminal management models, the simplest case is a small container terminal with one QC, one AGV and one ASC. During its operation, a distributed method is always used to control the equipment.

The structure of distributed control is shown in Figure 4, where one can see, that the interaction of different parts of the equipment follows the dynamics of a discrete event and the controller of each equipment for loading and unloading containers. The continuous dynamics of the object is controlled locally.

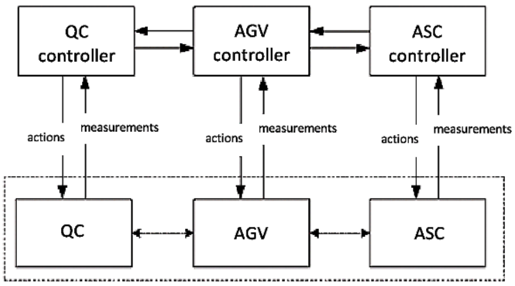


Figure 4. Dynamics of discrete events in a distributed control system

Energy efficiency is consistent with both load capacity and energy consumption. Power output depends on the dynamics of a discrete event, while energy consumption is determined by continuous time dynamics in which position and speed change over time. During formalization, the following rule should always be followed: in order to increase the energy efficiency of operational control at container terminals, the dynamics of discrete events and the dynamics of continuous time should be considered together.

It should be expected that at the operational level energy efficiency will be achieved for real-time operation. Unexpected operations (delays in work, imprecise arrival time of new containers, etc.) can change logistics processes of container transportation in real time and ultimately affect the energy efficiency of the container handling system.

For energy efficiency, a combination of discrete-event dynamics and continuous-time dynamics, called hybrid systems, can be smoothly modeled using interconnected hybrid models.

Since the studied system, presented in fig. 4, includes a combination of discrete event dynamics and continuous time dynamics, it is possible to represent the dynamics using the theory of hybrid automata [18]. The general model was formulated as

$$H = f\left(S, X, U, f, Init, Inv, E, G, R\right) \quad (1)$$

S – final set of discrete operational modes; X – final set of continuous state variables; U – final set of control variables; f: $S{\times}X{\times}U$ – describes evolution of continuous variables in a certain discrete mode of operation; *Init* – set of possible initial states; *Inv:* $S \rightarrow P(X)$ describes an invariant set that defines possible regions of continuous variables in a certain discrete mode of operation, where *P(X)* denotes the power set (set of all subsets) of *X*; *E*: *S*×*S* – set of boundaries representing possible switches between discrete modes of operation; *G* = *G*(*sα*, *sβ*): *S* → *P(X, U)* limiter, which provides conditions for transition of the operation discrete mode from s^{α} to s^{β}; *R: E × X → P(X)* – limiter that resets continuous variables between discrete mode switches.

In this case, sets of interconnected hybrid automata are considered. Automata interact through constraints: transitions between certain discrete modes are possible only when delays containing variables from several automata are fulfilled. For this, it is necessary to expand the description of the general hybrid automaton. A hybrid interconnected automaton was described as

$$H^{inter} = f\left(S, X, U, f, Init, Inv, E, G, R, V, G^{inter}\right) \tag{2}$$

V – final set of variables of other hybrid automata; $G^{inter} = G^{inter}(s^{\alpha}, s^{\beta})$: *S* → *P (X, U)* – connecting function that includes variables from *X*, *U* and *V*.

In an interconnected hybrid automaton, the discrete mode of operation *S*, the state variables *X*, and the state variables *V* can cause the relationship of G^{inter} functions. G^{inter} indicates a function in which another interacting device is involved. After G^{inter} is activated, the discrete mode can be switched between each other. By formulating the values of *V* and G^{inter}, the interaction between the two machines can be more clearly represented. For example, an interoperable function may represent the point at which a single container can be transferred from an *AGV* to an *ASC*.

There is a difference between controlled and uncontrolled components when a container is transported from a ship's berth to a stack in a storage area. *QC*, *AGV* and *ASC* are controlled components as the actions of these equipment elements should be determined by the control system. The vessel and storage location are uncontrolled components because they do not move when container is moved through the terminal.

3.2 *Modeling of controlled components.*

QCs, AGVs, and ASCs can be considered controlled components that transport a container between two points: the location where the component collects or accepts the container and the location where it loads or offers the container. This is shown in Figure 5 where controlled object picks up one container at position A and transports it from A to B where it would be then unloaded. The dynamics of one controlled object can be described as an interconnected hybrid automaton, which is shown in Fig. 6. The dashed line in Fig. 6 means that the interaction between system elements depends on the presence of another object.

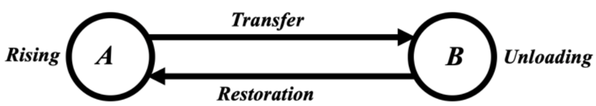


Figure 5. General model of controlled component

The details of the controlled type hybrid automaton were formulated as

$$H^{inter} = f\left(S_c, X_c, U_c, f_c, Init, Inv_c, E_c, G_c, R_c, V_c, G^{inter}\right) \tag{3}$$

$S_c \in \left\{s_c^1, s_c^2 s_c^3 s_c^4 s_c^5\right\}$ – discrete states of the system; $X_c \in \left\{x_c^{pos}(k), x_c^{vel}(k)\right\}\left(x_c^{pos}(k) \in \mathbb{R}, x_c^{vel}(k) \in \mathbb{R}\right)$ – set of continuous states: position $x_c^{pos}(k)$, $x_c^{pos}(k)$, m and velocity $x_c^{vel}(k)$, m/sec of the system component; $U_c \in \left\{u_c(k)\right\}$ – set of control variables representing the acceleration of the component, m/sec2; fc – function which describes continuous time dynamics in every discrete mode.

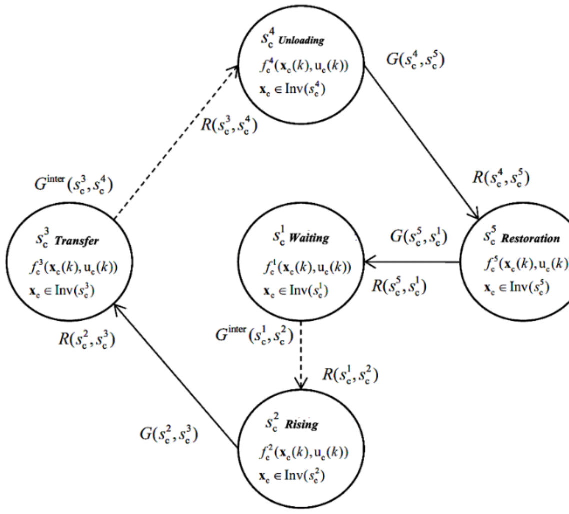


Figure 6. Hybrid automaton of the controlled object

The controlled component can be in one of five discrete states Sc. In state s_c^1 (waiting) – the controlled object is waiting for another interacting component to drag the container. In state s_c^2 (pickup) – picks up the container at point A. In state s_c^3 (transportation) – moves the container from point A to B. In state s_c^4 (unload) – unloads the container at point B if another interacting component is available for container unloading. In s_c^5 (return) mode, the object moves from B to A to take the container back to A.

In the following we define Δt as the sampling time and $x_c(k) = \left[x_c^{pos}(k) x_c^{vel}(k)\right]^T$. Then in state 1 (waiting), state 2 (pickup), and state 4 (unloading): the component's position and velocity are unchanged. Therefore, the continuous time dynamics with respect to these three states $f_c^1\left(x_c(k), u_c(k)\right)$, $f_c^2\left(x_c(k), u_c(k)\right)$ and $f_c^4\left(x_c(k), u_c(k)\right)$ was described as

$$x_c(k+1) = x_c(k) \tag{4}$$

In state 3 (transition) and state 5 (return) a double integrator can be considered for continuous time dynamics. This was done without considering resistance to air resistance and rolling resistance and therefore discretized the continuous-time dynamics in states 3 and 5, namely $f_c^3\left(x_c(k), u_c(k)\right)$ and $f_c^5\left(x_c(k), u_c(k)\right)$, was written as

$$x_c\left(k+1\right)=\begin{bmatrix}1 & \Delta T\\ 0 & 1\end{bmatrix}x_c\left(k\right)+\begin{bmatrix}0,5\Delta T^2\\ \Delta T\end{bmatrix}u_c\left(k\right) \quad (5)$$

For a given controlled component, the value of Inv_c was formulated as

$$Inv\left(s_c^1\right)=\left\{x_c^{pos}\left(k\right)=x_c^{unload}\right\}, \quad (6)$$

$$Inv\left(s_c^2\right)=\left\{x_c^{pos}\left(k\right)=x_c^{unload}\right\}, \quad (7)$$

$$Inv\left(s_c^3\right)=\left\{x_c^{load}\le x_c^{pos}\left(k\right)\le x_c^{unload}\right\}, \quad (8)$$

$$Inv\left(s_c^4\right)=\left\{x_c^{pos}\left(k\right)=x_c^{load}\right\}, \quad (9)$$

$$Inv\left(s_c^5\right)=\left\{x_c^{load}\le x_c^{pos}\left(k\right)\le x_c^{unload}\right\}, \quad (10)$$

x_c^{load} та x_c^{unload} – positions for loading and unloading containers; Ec – defining as the set $\left\{\left(s_c^1,s_c^2\right),\left(s_c^2,s_c^3\right),\left(s_c^3,s_c^4\right),\left(s_c^4,s_c^5\right),\left(s_c^5,s_c^1\right)\right\}$; Gc – interaction function of the controlled component; $s_c\left(k\right)$ – discrete state of the component at time k.

Interaction $G\left(s_c^1,s_c^2\right)=\left\{s_c\left(k\right)=s_c^1,x_c\left(k\right)=x_c^{load}\right\}$ depends on the presence of another component to pick up the container. This dependence is represented by the dashed line in Fig. 6.

When $G\left(s_c^2,s_c^3\right)=\left\{s_c\left(k\right)=s_c^2\right\}$ – the component finishes pick up.

When $G\left(s_c^3,s_c^4\right)=\left\{s_c\left(k\right)=s_c^3,x_c\left(k\right)=x_c^{unload}\right\}$ – component reaches the loading position and waits for unloading.

When $G\left(s_c^4,s_c^5\right)=\left\{s_c\left(k\right)=s_c^4\right\}$ – component completes unloading.

When $G\left(s_c^5,s_c^1\right)=\left\{x_c\left(k\right)=x_c^{load}\right\}$ – component reaches the loading position.

A continuous state does not change as a result of switching discrete states. That is why, $R_c=\left\{\left(x_c^-,x_c^+\right)\mid x_c^-\in\mathbb{R}^2,x_c^-\in\mathbb{R}^2\; ma\; x_c^-=x_c^+\right\}$.

The final set of variables Vc is associated with the variables of other hybrid automata interacting with it. The interaction state of variables of other hybrid automata is used to launch interconnected functions.

The G_c^{inter} function describes the interaction of controlled components with different hybrid systems simultaneously. In fact, this indicates that two G_c^{inter} of every interconnected hybrid automaton are connected.

QC, *AGV* and *ASC* are the controlled components. That is why $G^{inter}\left(s_c^\alpha,s_c^\beta\right)$ can be represented as $G^{inter}\left(s_{qc}^\alpha,s_{qc}^\beta\right)$, $G^{inter}\left(s_{agv}^\alpha,s_{agv}^\beta\right)$ and $G^{inter}\left(s_{asc}^\alpha,s_{asc}^\beta\right)$. In particular, container is transferred from the QC to the AGV, in which the initiators $G^{inter}\left(s_{qc}^1,s_{qc}^2\right)$ and $G^{inter}\left(s_{agv}^3,s_{agv}^4\right)$ are triggered simultaneously. Similarly, $G^{inter}\left(s_{agv}^1,s_{agv}^2\right)$ and $G^{inter}\left(s_{asc}^3,s_{asc}^4\right)$ are triggered simultaneously when a container is transported from *AGV* to *ASC*. Interrelated functions of controlled components are shown in table. 3.

Table 3. G_c^{inter} function with related functions

G^{inter}	Related G^{inter}
$G^{inter}\left(s_{qc}^1,s_{qc}^2\right)$	$G^{inter}\left(s_{agv}^3,s_{agv}^4\right)$
$G^{inter}\left(s_{agv}^1,s_{agv}^2\right)$	$G^{inter}\left(s_{asc}^3,s_{asc}^4\right)$

The dynamics of uncontrolled component can be described as a hybrid automaton with

$$H_{uc}=\left(S_{uc},X_{uc},U_{uc},f_{uc},Init_{uc},Inv_{uc},E_{uc},G_{uc},R_{uc}\right) \quad (11)$$

$S_{uc}=\left\{s_{uc}^1,s_{uc}^2\right\}$ – two discrete states in which uncontrolled component can be; $X_{uc}=\left\{N_{uc}\left(k\right)\right\}\left(N_{uc}\left(k\right)\in\mathbb{R}\right)$; $N_{uc}\left(k\right)$ – limited number of containers in this component; f_{uc} – represents dynamics of this uncontrolled component; E_{uc} – is defined as the set $\left\{\left(s_c^1,s_c^2\right),\left(s_c^2,s_c^1\right)\right\}$.

Let $x_{uc}\left(k\right)=N_{uc}\left(k\right)$. In discrete state s_{uc}^1 (action), one container is loaded or unloaded from this uncontrolled component. In discrete mode s_{uc}^2 (waiting), this component waits for a container. The dynamics of the uncontrolled component is shown in Fig. 7

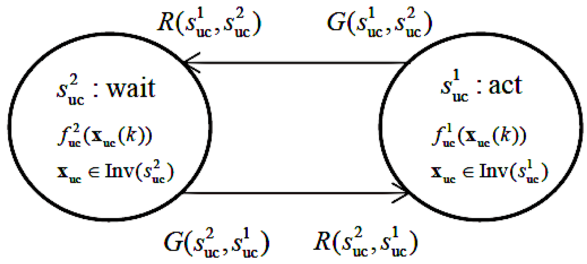


Figure 7. Hybrid automaton for uncontrolled component

The continuous dynamics of two discrete states is modeled as follows:

1. In state 1 (action), the number of containers changes and $f_{uc}^1 N_{uc}\left(k\right)$ can be written as

$$x_{uc}\left(k+1\right)=x_{uc}\left(k\right)+a_{uc} \quad (12)$$

$a_{uc}=-1$, if the container is on the ship; $a_{uc}=1$, if the container is stacked.

2. In state 2 the number of containers does not change and $f_{uc}^2 N_{uc}\left(k\right)$ can be written as

$$x_{uc}\left(k+1\right)=x_{uc}\left(k\right) \quad (13)$$

Inv_{uc} is then defined for this unmanaged component in the form

$$Inv\left(s_{uc}^1\right)=\left\{0\le x_{uc}\left(k\right)\le N\right\} \quad (14)$$

$$Inv\left(s_{uc}^1\right)=\left\{0\le x_{uc}\left(k\right)\le N\right\} \quad (15)$$

N – capacity of this component.

When $G\left(s_{uc}^1, s_{uc}^2\right) = \left\{ x_{uc}^{pos}(k) = x_c^{act} \right\}$ – the interaction depends on the arrival of the controlled component.

When $G\left(s_{uc}^2, s_{uc}^1\right) = \left\{ s_{uc}(k) = s_{uc}^1 \right\}$ – the processing of the container ends. $s_{uc}(k)$ is used to describe the discrete state of the uncontrolled component at time k.

A continuous state does not change as a result of switching discrete states. That is why $R\left(s_{uc}^1, s_{uc}^2\right) = R\left(s_{uc}^2, s_{uc}^1\right) = \left\{ N_{uc}^- = N_{uc}^+ \right\}$.

The G_{uc}^{inter} function describes interaction of uncontrolled components with controlled interconnected hybrid automata. The term uncontrolled can be replaced by vessel and stack to denote a vessel and a place of storage. In the simulation, $G_{inter}\left(s_v^2, s_v^1\right)$ and $G_{inter}\left(s_{qc}^3, s_{qc}^4\right)$ are connecting when the QC collects the container from the vessel. Also, $G_{inter}\left(s_v^2, s_v^1\right)$ and $G_{inter}\left(s_{qc}^3, s_{qc}^4\right)$ are synchronized when the ASC unloads the container onto the stack. These related conjugate functions are shown in Table 4.

Table 4. G_{uc}^{inter} with related functions

G^{inter}	Related G^{inter}
$G^{inter}\left(s_v^1, s_v^2\right)$	$G^{inter}\left(s_{qc}^3, s_{qc}^4\right)$
$G^{inter}\left(s_s^2, s_s^1\right)$	$G^{inter}\left(s_{asc}^1, s_{asc}^2\right)$

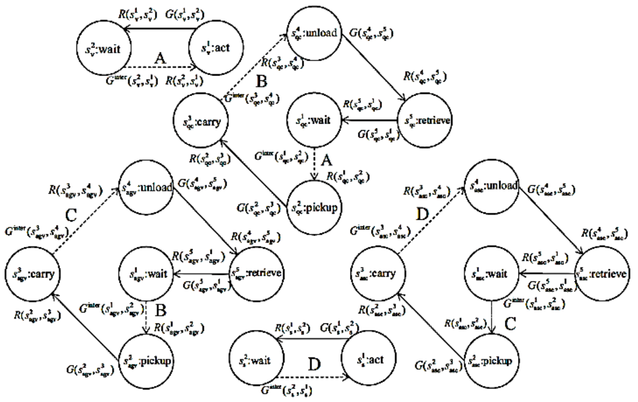


Figure 8. Simplified representation of the complete hybrid system

When a container is transported from a vessel's berth to a stack storage location, the *QC* and *AGV* interact in the berth area, while the *AGV* interacts with the *ASC* in the storage area. This interaction is shown in Figure 8. Five components are connected by interaction functions labeled *A*, *B*, *C*, and *D*.

The interaction between two different components, marked with letters *A*, *B*, *C* and *D* in fig. 8 allows us to conclude that two functions of two interacting components are realized and take place in time simultaneously.

For interaction A, when $G^{inter}\left(s_s^2, s_s^1\right)$ is triggered, the vessel make transition from the discrete state s_v^2 to s_v^1 to ship the container. At the same time $G^{inter}\left(s_s^2, s_s^1\right)$ and $G^{inter}\left(s_{qc}^1, s_{qc}^4\right)$ coincide when discrete state of the vessel would be changing from s_v^2 to s_v^1 to pick up the container. Similarly, the synchronization of two interacting components can be specified for *B*, *C*, and *D*.

The integration of the five components mentioned above forms a hybrid system, including continuous time linear dynamics and discrete event dynamics. Such a class of hybrid systems can be described as mixed logic dynamic systems. In such systems, part of continuous time is described by linear dynamics, and part of a discrete event is modeled as a set of linear constraints on dual variables and continuous variables. This type of model is very good for formulating control prediction model problems for hybrid systems.

3.3 *A model of mixed logic dynamic system.*

The general model of the mixed logic dynamic system was described by the following equations

$$\mathrm{x}(k+1) = \mathrm{Ax}(k) + \mathrm{B}_1\mathrm{u}(k) + \mathrm{B}_2\delta(k) + \mathrm{B}_3\mathrm{z}(k), \quad (16)$$

$$\mathrm{y}(k) = \mathrm{Cx}(k) + \mathrm{D}_1\mathrm{u}(k) + \mathrm{D}_2\delta(k) + \mathrm{D}_3\mathrm{z}(k), \quad (17)$$

$$\mathrm{E}_2\delta(k) + \mathrm{E}_3\mathrm{z}(k) \le \mathrm{E}_1\mathrm{u}(k) + \mathrm{E}_4\mathrm{x}(k) + \mathrm{E}_5, \quad (18)$$

To use it, input signals should have the following structure $x(k) = \left[x_r^T(k) x_b^T(k) \right]^T$ with $x_r(k) \in \mathbb{R}^n$ – continuous part of the state vector. $x_b(k) \in \{0,1\}^{n_b}$ – part of the state vector corresponding to the discrete part.

Output signals should have analogical structure $y(k) = \left[y_r^T(k) y_b^T(k) \right]^T$ with $y_r(k) \in \mathbb{R}^m$ – continuous part of the output and $y_b(k) \in \{0,1\}^{m_b}$ – discrete part of the output. y(k) – output vector.

The input vector $u(k) = \left[u_r^T(k) u_b^T(k) \right]^T$ consists of continuous part $u_r(k) \in \mathbb{R}^{l_r}$ and discrete part $u_b(k) \in \{0,1\}^{l_b}$.

z(k) – auxiliary integer; matrices *A*, *B1 ~ B3*, *C*, *D1 ~ D3* and *E1 ~ E4* denote real constant matrices; *E5* – real vector.

Written as the set of equations (16)-(18), the form of a mixed logic dynamic system during the simulation of terminal operation actually allows to solve the problem of the development of continuous variable functions using linear dynamic equations and discrete variables. It is possible to work with the help of described functions and their interaction with each other.

Boundary conditions for the model consist of x(k) values. Individual geometry described using x_c^{load} and x_c^{unload} can be mapped to a mixed logic dynamic system model. Uncertainties, such as delay of operations and exact arrival time of new containers, can be incorporated based on the mixed logic dynamic system model by measuring states and adding new variables.

4 RESULTS

4.1 *Centralized hybrid model of predictive management*

The term predictive control model refers to a control methodology that makes explicit use of dynamic model to derive control actions. In the predictive control model, a dynamic model was developed to predict the future state of the terminal system based on the current state and proposed future actions. Predictive control models can be applied to hybrid systems that simultaneously considers the dynamics of a discrete event and the dynamics of a continuous event. The general structure of the centralized hybrid model of predictive control is shown in Figure 9.

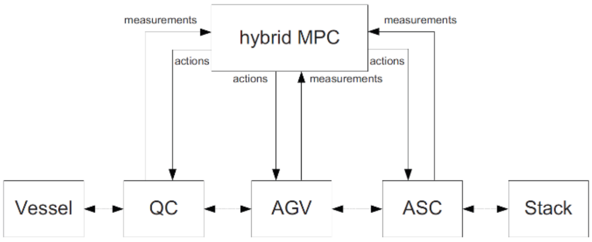


Figure 9. The structure of centralized hybrid model of predictive management

The aim of management is to transport containers from the vessel's berth and one stack using components, that presented in Fig. 9. The purpose of management is to balance the load capacity and energy consumption of the controlled components.

The problem of predictive management model was formulated in the following way

$$min\sum_{l=0}^{N_p-1}\left[J_1\left(x(k+l+1),u(k+l)\right)+J_2\left(x(k+l+1),u(k+l)\right)\right] \quad (19)$$

$$x(k+1+l)=Ax(k+l)+B_1u(k+l)+B_2\delta(k+l)+B_3z(k+l) \quad (20)$$

$$y(k+l)=Cx(k+l)+D_1u(k+l)+D_2\delta(k+l)+D_3z(k+l) \quad (21)$$

$$E_2\delta(k+l)+E_3z(k+l)\le E_1u(k+l)+E_4x(k+l)+E_5 \quad (22)$$

$$u_{min}\le u(k+l)\le u_{max} \quad (23)$$

$$x_{min}\le u(k+l+1)\le x_{max} \quad (24)$$

$$y_{min}\le u(k+l)\le y_{max} \quad (25)$$

$J_1\left(x(k+1),u(k)\right)=N_v(k)-N_s(k)$; $J_2\left(x(k+1),u(k)\right)=\lambda_1\left|u_{qc}(k)\right|+\lambda_2\left|u_{agv}(k)\right|+\lambda_3\left|u_{asc}(k)\right|$; $N_v(k)$ – describes containers on the ship; $N_s(k)$ – describes containers in the stack; $u_{qc}(k)$, $u_{agv}(k)$ and $u_{asc}(k)$ – accelerations of *QC*, *AGV* and *ASC*, respectively; N_p - forecast horizon; $x(k+l+1)$ – predicted state at time $k+l+1$ based on input $u(k+l)$.

It should be noted that weights λ_1, λ_2 and λ_3 are used to balance the loading power and energy consumption. At the same time, u_{min}, u_{max}, x_{min}, x_{max} and y_{min}, y_{max} are the boundaries on inputs, states and outputs, respectively.

The function $J_1\left(x(k+1),u(k)\right)$ is dedicated to consider the problem of overload power management. The vessel is emptied as quickly as possible, minimizing $N_v(k)$, but this parameter cannot guarantee the arrival of the last container in the stack after it was removed from the vessel. The value $N_s(k)$ is added to J_1 to ensure that last container arrives in the stack.

The function $J_2\left(x(k+1),u(k)\right)$ is dedicated to consider the process of simplifying the consumption of kinetic energy of all controlled components. Continuous time dynamics is a double integrator that ignores air resistance and rolling resistance. For this reason, the absolute value of acceleration is considered as a cost criterion arising from the problem of optimal fuel management. This fuel-optimal criterion makes it easier to solve the optimization problem.

In the objective function of the proposed hybrid predictive control model, the processing part J_1 and the energy-efficient part J_2 can be balanced by changing λ_1, λ_2 and λ_3.

Considering that

$$\tilde{u}(k)=\left[u(k)^T,u(k+1)^T,\ldots,u(k+N_p-1)^T,\delta(k)^T,\delta(k+1)^T,\ldots,\delta(k+N_p-1)^T,z(k)^T,z(k++1)^T,\ldots,z(k+N_p-1)^T\right]^T$$

time step k can be formulated as

$$\min_{\tilde{u}(k)} f_0^T\tilde{u}(k)+\lambda f_1^T\tilde{u}(k)+\lambda f_2^T\tilde{u}(k)+\lambda f_3^T\tilde{u}(k), \quad (26)$$

(26) was written under the condition that

$$b_{min}\le\tilde{A}\tilde{u}(k)\le b_{max}, \quad (27)$$

$$\tilde{u}_{min}\le\tilde{u}(k)\le\tilde{u}_{max} \quad (28)$$

f_0 – relates loading capacities to the objective function; f_1, f_2 and f_3 – spending related to energy consumption by *QQ*, *AGV* and *ASC*, respectively; b_{min} and b_{max} – lower and upper boundaries of the corresponding inequality; $\tilde{u}_{min}$ and $\tilde{u}_{max}$ – lower and upper limits of the controlled variables.

In the objective function (26), the scale $f_0^T\tilde{u}(k)$ will be much larger than $f_1^T\tilde{u}(k)$, $f_2^T\tilde{u}(k)$ and $f_3^T\tilde{u}(k)$.

To reduce the share of loading power and keep the cost of operation in a relatively constant range, it is necessary to use the adaptive weight $\left|f_0^T\tilde{u}(k-1)\right|$. In this case, the effect of λ on power consumption and throughput can be seen more clearly. The new objective function in this case can be written as

$$\min_{\tilde{u}(k)}\frac{f_0^T\tilde{u}(k)}{\left|f_0^T\tilde{u}(k-1)+\varepsilon\right|}+\lambda(f_1^T\tilde{u}(k)+f_2^T\tilde{u}(k)+f_3^T\tilde{u}(k)) \quad (29)$$

ε is a very small number in the case $f_0^T\tilde{u}(k-1)=0$.

In the formulated objective function (29), the variable λ can affect the energy consumption and throughput of a piece of equipment.

The function of controller is to obtain the minimum time for each operation and assign specific equipment to perform them. Considering one *QC*, we denote the time limits for two operations at stage 1 as $\left[t_{start,i}^{11}, t_{end,i}^{11}\right]$.

In the second stage, there is no difference between selection of certain equipment because all *AGVs* are identical. We define $\Psi_{agv} = \{1, 2, \ldots, n_{agv}\}$, which represent a set of *AGVs*.

$$f_{agv} : \Phi \rightarrow \Psi_{agv} \tag{30}$$

f_{agv} – function that depicts a set of tasks Φ for *AGV* by the number Ψ_{agv}.

Function $f_{agv}(i)$ describes the specific *AGV* assigned to work *i*. The time limits for work *i* were written as $\left[t_{start,i,f_{agv(i)}}^{21}, t_{end,i,f_{agv(i)}}^{21}\right]$ and $\left[t_{start,i,f_{agv(i)}}^{22}, t_{end,i,f_{agv(i)}}^{22}\right]$.

In the case of *ASC*, scheduling of work *i* is determined in advance, since each container has a specific position on the ship and a specific destination in the stack. For this reason, the function $f_{asc}(i)$ was used to describe the assigned *ASC* for job *i*. The time limits of operation i for a certain *ASC* were written as $\left[t_{start,i,f_{asc(i)}}^{31}, t_{end,i,f_{asc(i)}}^{31}\right]$ and $\left[t_{start,i,f_{asc(i)}}^{32}, t_{end,i,f_{asc(i)}}^{32}\right]$.

The time of cargo operations $t_i^{h_1h_2}$ depends on the initial time values of a_i, b_i and c_i. The time intervals of operation $O_i^{h_1h_2}$ in three stages are shown in table 5. We enter: $t_{start,i}^{h_1h_2}$ – start time of the work and $t_{end,i}^{h_1h_2}$ – time of the end of the corresponding cargo operation $O_i^{h_1h_2}$ ($h_1 \in \{1,2,3\}$, $h_2 \in \{1,2\}$).

Table 5. Time intervals of operations $O_i^{h_1h_2}$ at three stages

Operation	Equipment	Time of start	Time of end	Operation execution time
O_i^{11}	*QC*	a_i	$a_i + t_i^{11}$	t_i^{11}
O_i^{12}	*QC*	$a_i + t_i^{11}$	$a_i + t_i^{11} + t_i^{12}$	t_i^{12}
O_i^{21}	*AGV*	b_i	$b_i + t_i^{21}$	t_i^{21}
O_i^{22}	*AGV*	c_i	$c_i + t_i^{22}$	t_i^{22}
O_i^{31}	*ASC*	c_i	$c_i + t_i^{31}$	t_i^{31}
O_i^{32}	*ASC*	$c_i + t_i^{31}$	$c_i + t_i^{31} + t_i^{32}$	t_i^{32}

At the lower level, the controller provides management of each device and makes decisions about the continuous trajectory of a piece of equipment. In each controller at the lower level, the task of optimal control should be formulated in a form which gives an ability to finish the operation within the set working time. A lower-level controller may consider additional objectives, such as minimizing energy consumption. The specific task of equipment management depends on the operation it should perform.

Let $r_0 = [r_0\ 0]^T$ $r_f = [r_f\ 0]^T$ describes initial position and destination of the equipment. In cargo operations, the corresponding piece of equipment will move from r_0 to r_f within a given time. This management optimization problem can be presented in the form

$$\min_{u(t)} J\left(r(t), u(t)\right), \tag{31}$$

with condition of fulfillment of the following equations

$$\dot{r}(t) = g\left(r(t), u(t)\right), \tag{32}$$

$$r(t_0) = r_0, r(t_f) = r_f, t \in \left[t_0, t_f\right], \tag{33}$$

$J\left(\left(r(t), u(t)\right)\right) = \int_{t_0}^{t_f} 0{,}5 m r_2(t)^2$ – function that quantifies the energy consumption of equipment with mass *m* and speed r_2.

The terminal equipment starts its work at t_0 and should finish it before t_f. The initial and final states in equation (33) ensure that operation is complete.

To solve the problem of optimal control (31), an analytical approach was used, where optimal solution is obtained by reducing to the corresponding extremum the quadratic function of energy consumption, considering, that the general system model is linear.

The aim of control optimization is to minimize the mechanical energy of a piece of equipment when moving from initial position r_0 to final t_f during corresponding time interval (from t_0 to t_f) for the operation $O_i^{h_1h_2}$. For discretization, time step was written as ΔT, and then $\frac{t_i^{h_1h_2}}{\Delta T} + 1$ – number of time steps for the time interval from t_0 to t_f. The discrete dynamic model based on (32) and (33) for the part of port terminal equipment was written as

$$r(k+1) = \begin{bmatrix} 1 & \Delta T \\ 0 & 1 \end{bmatrix} r(k) + \begin{bmatrix} 0{,}5\Delta T^2 \\ \Delta T \end{bmatrix} u(k) = Ar(k) + Bu(k), \tag{34}$$

$r(k) = [r_1(k)\ r_2(k)]^T$ describes position $r_1(k)$ and the velocity $r_2(k)$ of the piece of equipment, $u(k)$ – acceleration of the piece of equipment.

To minimize the mechanical energy of the equipment from $k = 0$ to $k = N_s$ considering its dynamics and limitations, after calculating $u=[u(0), u(1), \ldots, u(N_s-1)]^T$, the optimization problem was formulated as follows:

$$\min_u \sum_{k=1}^{N_s} 0{,}5 m \left(r_2(k)\right)^2, \tag{35}$$

with condition that $k = 0, 1, \ldots, N_s-1$, and also provided that are realized equalities

$$r(k+1) = Ar(k) + Bu(k) \tag{36}$$

$$r_{min} \le r(k) \le r_{max} \tag{37}$$

$$u_{min} \le u(k) \le u_{max} \tag{38}$$

$$r(0) = r_0, r(N_s) = r_f \tag{39}$$

$0,5m\left(r_2\left(k\right)\right)^2$ describes the kinetic energy at the time moment k; r_{min} and r_{max} – restrictions on $r(k)$ states; u_{min}, and u_{max} – limits of control variable $u(k)$.

At the moment when problem of minimizing the mechanical energy of equipment is solved, the lower-level controller will set the calculated trajectories as a reference for the part of equipment.

To plan operations with a hierarchical management system it is necessary to determine the minimum time required for a processing operation with one piece of equipment. This time depends on condition and continuous dynamics of equipment. Its numerical value can be obtained using the theory of optimal control due to the use of Pontryagin's maximum principle [2]. Applying the principle gives a control action $u(t)$ that minimizes time to complete the task. This control action $u(t)$ was written as

$$u\left(t\right)=\begin{cases}-u_{max} & \text{for } t=t_2^+,\ldots,t_b\\ 0 & \text{for } t=t_1^+,\ldots,t_2^-\\ u_{max} & \text{for } t=0^+,\ldots,t_1^-\end{cases}, \tag{40}$$

where t_1 and t_2 are the variables which determine acceleration.

At the same time, $t_1^+\geq t_1+\varepsilon$, $t_2^+\geq t_2+\varepsilon$, $t_1^-\geq t_1-\varepsilon$ and $t_2^-\geq t_2-\varepsilon$ (where ε is a small positive number), and t_1 and t_b are calculated as

$$t_1=\begin{cases}\dfrac{v_{max}}{u_{max}} & \text{if } d_t\geq\dfrac{v_{max}^2}{u_{max}}\\ \sqrt{\dfrac{d_t}{u_{max}}} & \text{if } d_t<\dfrac{v_{max}^2}{u_{max}}\end{cases}, \tag{41}$$

$$t_b=\begin{cases}2\dfrac{v_{max}}{u_{max}}+\dfrac{d_t-\dfrac{v_{max}^2}{u_{max}}}{v_{max}} & \text{if } d_t\geq\dfrac{v_{max}^2}{u_{max}}\\ 2\sqrt{\dfrac{d_t}{u_{max}}} & \text{if } d_t<\dfrac{v_{max}^2}{u_{max}}\end{cases}, \tag{42}$$

The minimum time depends on the ratio between d_t and $\dfrac{v_{max}}{u_{max}}$. Thus, the minimum time required for treatment operation with one piece of equipment can be obtained from the Pontryagin maximum conditions.

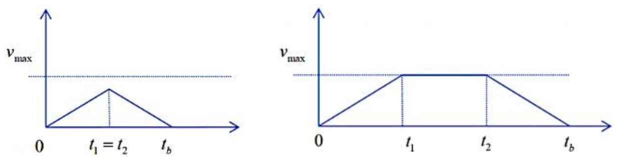


Figure 10. The minimum working time for the distance dt

Different plots of the minimum time to complete the work depending on the distance dt are shown in Figure 10. When $d_t<\dfrac{v_{max}}{u_{max}}$ (Figure 10-a) and when $d_t\geq\dfrac{v_{max}}{u_{max}}$ (Figure 10-b).

The hierarchical system emphasizes the interdependence of the planning problem regarding the dynamics of discrete events of all port terminal equipment units and task of optimal control regarding individual equipment elements considering dynamics of continuous time. When using it, it is important to display correctly dynamics of discrete events with dynamics of continuous operation of a particular type of equipment. In this case, the use of a constant movement velocity when calculating equipment's operational time can lead to difficulties in controlling the equipment. Examples of such error are when dynamics and hardware limitations (such as velocity and acceleration) are considered.

4.2 *Simulation results*

During simulation of the hybrid system in the port terminal management model, as a container terminal was taken variant which contains three QCs, four AGVs, and four ASCs. It was accepted that a distributed method is used to control the operation of all equipment during terminal operation. Throughout the modeling process, the operational management of container terminal was focused on the dynamics of discrete events during planning. Optimal control of equipment based on the centralized hybrid model of predictive control was considered as an option for obtaining the minimum period of time for the all works completion. This parameter was considered as the final result of numerical calculations. The time of work completion was determined in accordance with the second main indicator of the port terminal operation - total energy consumption.

Simulation was carried out with consideration of different options for containers position on the ship. Systematization of results was carried out in comparison with energy efficiency indicators for two options for container transportation.

The first transportation option corresponded to the case of closest choice, when the sequence of N jobs σ_{ij}^1 at stage 1 ranged from the nearest to the farthest place on the container ship.

The second variant of transportation corresponded to the case of random selection, when the sequence of N workplaces σ_{ij}^2 at stage 1 was determined randomly.

Table 6. The time of all works completion in relation to different approaches to terminal operation, sec

Test No.	Optimal	Nearest	Random
1.	477	477	496
2.	476	542	552
3.	496	573	540
4.	478	502	478
5.	476	516	504
6.	496	546	520
7.	478	551	488
8.	476	570	543
9.	481	476	532
10.	467	490	539
Average	480.1	524.3	519.2

Ten independent tests were conducted, as a result of which sufficiently characteristic data were obtained. The generalized simulation results are shown in Table 6 and from the main efficiency indicator point of view they are displayed in the form of the most important result - time of works completion in relation to different approaches of terminal operation.

Figure 11 shows how the variance of the work execution time D is distributed in all ten cases of the test simulation. Each vertical section corresponds to a separate modeling case. Red bars answer to the first transportation option - the nearest container, black bars answer to the second transportation option - random container selection, blue bars answer to the developed transportation option - a hybrid model of managing the process of container selection and transportation.

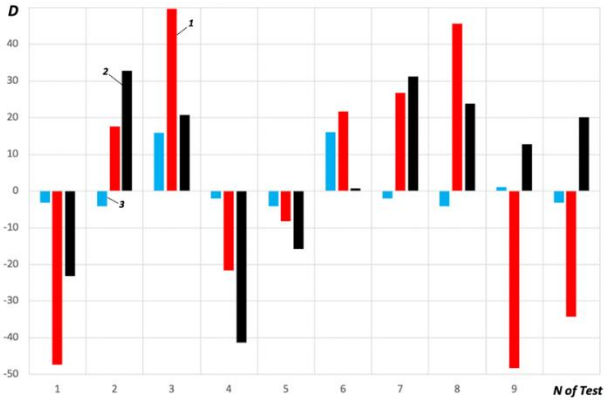


Figure 11. Distribution of time variance D for three variants of container selection and transportation. 1 – selection of the nearest container, 2 – random selection of container, 3 – hybrid model of container selection and transportation.

The analysis of the displayed results allows us to formulate an unequivocal conclusion that the same result was obtained in nine out of ten simulations - the hybrid control model was always characterized by the shortest time to achieve the final result. The variance was minimal in all nine cases of terminal operation only in that case when the centralized hybrid predictive control model developed during the research was used to control its operation.

Table 7 shows the results generated using an energy-saving schedule with optimal functioning of the terminal due to the operation of the equipment based on the centralized hybrid model of predictive control. The indicator of energy costs, as it possible to see, is very low.

Table 7. Performance indicators of the hybrid management model

Test No.	Work completion time, s	Energy consumption, kW
1.	477	4.82
2.	476	7.05
3.	496	8.82
4.	478	5.15
5.	476	5.13
6.	496	6.54
7.	478	4.97
8.	476	7.61
9.	481	6.76
10.	467	6.29
Average	480.1	6.314

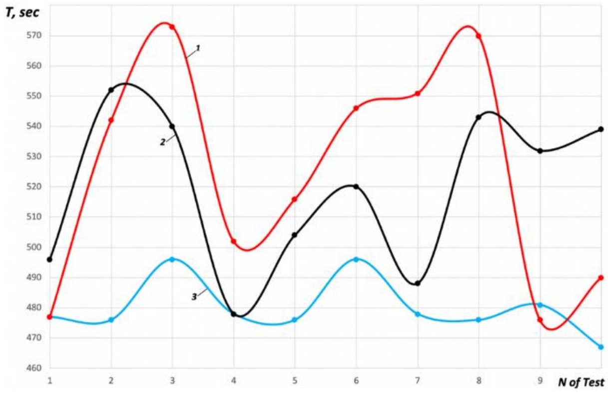


Figure 12. Time of works completion. 1 – selection of the nearest container, 2 – random selection of container, 3 – hybrid model of container selection and transportation.

Comparative analysis of results that describing work completion time is shown in Figure 12. The graph shows that the deviation of the time for carrying out a set of container handling operations on a ship from the optimal value invariably in all modeling cases corresponded to the hybrid control model (Figure 12, curve 3)

This result is quite non-standard since it is logical to assume that the best result should correspond to the closest time for every operation completion. The graph clearly shows that the smallest time oscillations correspond to the hybrid control model. The amplitude of the deviation is minimal and, in general, the transition from one point to another is smooth, unlike the first and second options for controlling the process of operating a port container terminal. The graph shows that the curves that correspond to the first and second control options gave an almost negative result in terms of the quality of logistics for container movement through the transport terminal. Sudden jumps in time indicate obvious operational problems in management. The third operating option, based on a hybrid control model, is the most effective because it is characterized by an almost complete absence of pulsations and has minimal numerical indicators.

The analysis of received simulation data allows us to draw an unequivocal conclusion - the centralized hybrid model of predictive control under all constant conditions allows to obtain the best performance of the terminal in comparison with standard methods of managing the process of unloading containers from a ship. The time to complete the work in this case is the shortest, and the energy consumption is minimal.

5 DISCUSSION

The whole investigation described in the article was devoted to solution of one problem – to arise operational quality of the container terminal. The centralized hybrid model of predictive management showed very high results, but the main issue from the point of view of port's operation profitability remains the issue of automation of its operation management. Terminal automation involves a high investment cost, but is offset by a reduction in operational costs. By developing its infrastructure, terminal capacity increases and operating costs decrease due to increased supply. Usually, ports with more than one terminal operate at more competitive prices and therefore have more lines of service for ships and users in general.

The operating costs of a container terminal can be reduced by investing in automation. Fixed costs (port tariffs, state taxes, salaries, etc.) in ports, although they increase over a long period, are practically constant and do not depend on how many ships docked each month or how many movements were made at the berth. Variable costs are related to the level of terminal service and are very flexible and easily changed to provide different levels of service. These costs can also vary in the short term and thus constitute a large-scale scenario for further terminal automation.

The main direction of further research in this way can be described as: if variable costs of container terminal can be reduced, then in all ports they can be improved in the direction of the costs of cargo operations.

If one considers all operations related to maneuvering, mooring, wiring and security of vessels, the total cost of arrival of one vessel can reach 14,000 USD, which is partly explained by the high risks associated with mooring operations. Improvement due to the automation of berth equipment operating on the basis of the centralized hybrid model of predictive management proposed in the article can reduce risks and associated costs. In this case, the services related to shipping of vessels may be reduced up to 50% of the total cost of vessel's arrival.

Terminal automation, which contributes to the reduction of operating costs, also includes the amount of fuel, electricity, materials and human resources used by machines. This direction of spending can make up to 60% of the total cost of cargo handling of containers and it is very promising from the point of view of terminal automation. Due to the introduction of new automatic systems, it is possible to reduce the total number of terminal operators and minimize the cost of handling containers. The main obstacle in this case can be the legislation on unemployment.

For the case of investment research, which requires only initial spending, and then immediately begins to provide income, it is recommended to use the following equation

$$NPV = \left[\sum_{t=0}^{T} \frac{S_t}{(1+i)^t} \right] - i_0 \tag{43}$$

T – quantity of years; S_t – net monetary flow in the period; i – discount rate for one year; i_0 – amount of initial investment.

Return on Investment in the case of high values of the obtained return on investment means a high return that will be received by the investors who financed the project. Evaluation of return on investment can be done as

$$ROI_t = \frac{\sum_{t=1}^{T} \pi_t}{P_t} \tag{44}$$

π_t – profit received in each year; P_t – initial investments.

In the optimal case of using new terminal automation systems which are operating using the proposed centralized hybrid model of predictive control, equations (43) and (44) should give identical results, but the first indicator (NPV) is more qualitative and safer from the financial point of view.

As the main factors when assessing the level of necessary investments in terminal automation, it is possible to recommend an assessment of three directions: the terminal operating system; if there is a need for new equipment; changes in the terminal infrastructure (coverage of the terminal territory depending on the pressure of new cranes, alignment of paths, increase of territory in the area of berths, etc.).

Secondary factors that should be investigated during terminal automation include: industrial development of the country; labor cost; type of existing road surface; dimensions of terminal; technical specification and quality of necessary equipment; production costs compared to other countries; order sizes (scale effect).

During automation of terminal, every relevant detail of the port should be considered. It will give an ability in feature to estimate the necessary reductions in operating costs to balance the capital investment in automation.

6 CONCLUSIONS

The research described in the article is of significant practical importance as it gives an ability in feature to develop new concepts of automation of cargo operations due to the improvement of: modern port terminal management systems, terminal operating systems, decision support systems, technological planning of logistics schemes for handling container ships.

The use of the proposed centralized hybrid model of the predicted management of cargo handling process in seaports will lead to an even greater reduction in injury rates. This will happen due to the fact that the developed concept of the hybrid management system makes it possible to consider such features of the process of unloading cargo from the ship, which until now have not been considered yet. An example of one of the indicators is the movement velocity of all system elements depending on various external factors - weather conditions, the current time of day, the number of workers in the dangerous zone.

Centralized hybrid model of predictive control under all constant conditions allows to obtain the best performance of the terminal in comparison with standard methods of managing the process of unloading containers from a ship. The time to complete the work in this case is the shortest, and the energy consumption is minimal.

Terminal automation involves a high investment cost, but is compensated by a reduction in operating costs. By developing its infrastructure, terminal capacity increases and operating costs decrease due to increased supply. The choice of the terminal operating system, the need for new equipment, changes in the terminal infrastructure are the main factors on which investments depend.

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