

Hierarchical Management System for Container Vessels Automated Cargo Handling

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Abstract

Hierarchical management system is the next step for the development of container terminals all over the planet. The existing restrictions in transshipment operations are difficult to predict and invariably lead to a decrease in the terminal's throughput. The authors show that in modern control systems for the operation of a port container terminal, most of the automated processes use imperfect work algorithms and require optimal control based on the development of new approaches. The hierarchical multi-level control system proposed in the work, in comparison with traditional control methods, allows to reach the level of minimum energy consumption with the highest possible speed of containers unloading from the ship. For this control system, the authors formulated a model, an algorithm for implementing the work of control controllers and set optimal levels of control over work processes.

Keywords: Hierarchical management system, Port container terminals, Multi-level control system, Operational characteristics

1. Introduction

In recent 20 years could be observed rapid development of container ships with a cargo capacity exceeding 18,000 TEU, and this requires the development of new technologies for their cargo handling. A characteristic example in this case is parking time which grows disproportionately. When the cargo capacity of ships increases from 14,000 to 21,000 TEU, i.e. by 50%, the period of standing time required for complete overloading of the vessel increases by 150% [1].

The concentration of limited transshipment capacities of ports on the processing of "mega-vessels" leads to decrease in their throughput capacity. For this reason, almost all large terminals on the planet are increasingly turning to the modernization and technical support of the vessel's cargo handling processes. A significant part of these processes cannot be predicted and requires the use and sometimes the development of new methods for effective management, as well as requires a decision making in the shortest possible time.

2. Materials and Methods

2.1. Analysis of Trends in Automation of Container Processing Processes

Automated container terminals allow to increase significantly throughput and reduce operating costs. In comparison to general terminals where management is carried out by personnel, this fact is explained by the advantage of using improved automated equipment - automated vehicles, automatic stacker cranes (ASC), etc. Commonly known automatic container terminals in Europe are: Delta ECT (Europe Container Terminals), ECT Euromax, RWG (Rotterdam World Gateway) and HHLA (Hamburger Hafen und Logistik AG). A similar trend is observed in other ports of the world [2]. In China, the first fully automatic terminal of Qingdao QQCTN (Qingdao New Qianwan Container Terminal) entered operation in May 2017.

Cargo handling processes at the terminal can be divided into three types: wharf, warehousing and surface transportation operations. In most cases, containers at terminals with



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automatization are handled with a use of big quantity of automatic equipment: remotely controlled quay cranes (QC), automated guided vehicles (AGV) and ASC. So, e.g., the Delta ECT terminal in Rotterdam has 36 QCs, 265 AGVs and 137 ASCs. The terminal's annual electricity consumption is about 45,000 MWh. with an annual transshipment volume of 4,300,000 TEU. The terminal produces 71,300 tons of CO₂ per year [3].

The development of terminal automation is constant, as almost every year is marked by new developments and new technologies for their use. GPS-based AGV, e.g., provides free behavior and significantly reduces travel time in comparison to standard operational path, or the path guided by different computer operated optical systems. We can state that freedom of AGV behavior enhance the complexity for managing operations inside terminal. From one side, preventing two AGVs from colliding have to be taken into account to provide safety operation. From another side, AGVs interact with different types of equipment (such as QC and ASC) during cargo transportation to or from vessel.

During analysis of terminals functioning, the level of security of their operation is also of particular importance. The operation of almost all non-automated terminals falls under the conclusion that work in the port is extremely dangerous. A typical example for such a conclusion is the work [4], which focuses on the trends of increasing the level of security and studies the possibility of obtaining additional advantages in the field of security by increasing the automation level of container terminals. This article examines the incidence of injuries in ports at the United States West Coast and predicts that frequency of injuries due to the introduction of automation will steadily decrease over time.

2.2. Technical and Operational Characteristics of Equipment

Main part of the automated terminals is focused on the use of automated stacking cranes (Automated Stacking Crane, ASC). The main reason for this fact is a good compatibility of these cranes with various types of automated transport.

For ASC, a stacking height of 6 tiers has become standard. 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, ASCs are not efficiently operated because of the significant price of the facility itself. In a long row the processing time of containers increases significantly. Port terminals in all ports, with the exception of the two in Hamburg, use two identical ASCs on the same set of tracks.

The stacking geometry of modern terminals with ASC is variable. The general majority includes a scheme for placing

containers perpendicular to the berth. In recent years, the scheme of parallel arrangement for containers rows along the wharf has started to be used. The width of container rows is almost always equaling the range of eight to ten containers. The exception is the CTA and CTB terminals in Hamburg, which use a scheme of twelve container rows.

3. Management of Terminals

3.1. Problems of Effective Management of Automated Cargo Handling Processes

Three levels of problems are distinguished at container terminals: strategic, tactical and operational, depending on the time limits required to solve certain tasks of this level [5].

Problems solution at the first level concerns the layout of container terminal. At this level should be realized a pick-up of all necessary equipment that will be used for several years. Zhen et al. [6] had compared two different automated port terminals and for these two types he received a quantitative evaluation of their effectiveness; Vis and de Koster [7] had carried out a technical and economic analysis of automated vehicles such as AGV and ALV.

- Tactical problems tend to focus on the level which is answering to equipment capacity and state the amount of facilities needed to complete works expeditiously, ranging from days to months. Alessandri et al. [8] propose a dynamic approach to determine a correct part of available resources of a specific carrier of one modality. He has done it with a use of flow model based on discrete time. The required quantity of AGVs for container terminal which is partially automated was found out with the use of minimum flow algorithm [9].

At the operational level for the time interval from a few minutes to days, the detailed operation of the container handling equipment is decided. This problem solution includes the choice of processing means and the route for containers transportation within the terminal.

In [10], at the operational level, approaches to the solution of container terminal management tasks were classified as: software-based approaches (object-oriented approaches; agent-oriented approaches); analytical approaches (equipment planning; transport assignment; route determination).

Programming-based approaches are used to depict the behavior of container handling facility in an automated container terminal. In the category of programming approaches as the main concepts could be stated object-oriented and agency-oriented languages.

Object-oriented approaches provide a computer model using the concept of "object" characterized by a set of

attributes and methods [11]. Each terminal component (e.g. a single device or vessel) can be considered as an object. Connection of the objects answering to the different equipment is a basis for creation of container terminal [12].

On the basis of object-oriented programming, Duinkerken and Ottjes [13] developed a simulation model. It was done for automated container terminal. Their large-scale terminal was created on the technological traffic management system and for routing this system provides high level safety. The detailed model of the container terminal which was created with the use of object-oriented Plant Simulation model [14] is used to analyze the performance of container terminals. Governing parameter in this model is varying speed of the facilities.

Agent-oriented programming as a main concept uses term "agent" and in the following multiple agents are cooperating between themselves. In this type of programming "agent" answering to computer system which by its own have an ability to act independently on behalf of its user or owner. This system which actually is multi-agent system consists of a number of agents that can communicate with each other by exchanging messages [15].

Henesey [16] proposed a multi-agent approach. Its purpose is to enlarge the efficiency of container terminal by enlarging the capacity of available resources. Disadvantage of this solution is that the main attention is paid to the multi-agent interconnection between the components of the container terminal facilities, but not to the algorithm which regulate control and optimization operational mode of the facility. In other work, Henesey et al. [17] used simulator with "agents" and calculated operational modes when overloading containers with real parameters.

Xiao et al. [18] proposed an apportioned agency system for terminal traffic planning and berth allocation planning. In their system, coordination and cooperation refer to the berth allocation which does not consider a precise coordination between individual parts of facility at the current level of operation.

In addition to software approaches, there are analytical models for mathematical optimization of those operations where equipment planning and transport facilities management are usually considered apart from each other [19]. Facility scheduling is strongly related to the ship's service time and can determine operation and routing of equipment at a given time.

At container terminals, ship service time is the main productivity factor for terminal operators [20]. Because of this reason, the equipment of the automated container port terminal should be used in the optimal way to minimize the time to complete the processing of containers.

Considering the complex structure of automated container terminal operation specific areas (e.g. berths) should be considered to simplify the overall layout of the equipment. For a berth area, the planning task determines the sequence of QC work tasks and the optimal operational time intervals at which they can be completed [21], taking into account the different objectives and constraints of different operations.

In most cases, the problems of assigning a vehicle at a berth are considered under uncertainty conditions to adjust online changes in the terminal environment. The AGV administration problem is mainly treated as an individual research problem and during its solution various simplifying procedures are used. Despite of this, because of the strong interrelationship with the coastline area, loading capacity at the berths must be clearly defined, taking into account a certain algorithm for administrating AGVs.

The routing problem is an important problem. It usually focuses on avoiding collisions and deadlocks between all types of autonomous vehicles. Kim [22] has developed an effective algorithm for predicting and preventing deadlock situations with AGVs. Zeng [23] has described routing algorithm to avoid collisions by giving an ability to vehicles to variate their speed during interaction.

3.2. Types of Container Terminal Operations Management Systems

In our research container terminal was considered as a system which is large-scale and inside of it every different part of facility possesses its own dynamics. Work of various components have to be coordinated among themselves individually.

As a system container terminal consist of large number of subsystems and their control causes many difficulties for management. To solve these problems, there are systems of distributed and hierarchical control. They are applied in various transport areas, such as water and transport networks [5].

During the research, three types of container terminal management were identified: centralized, distributed, hierarchical.

The hierarchical type of control refers to the situation when local controllers are dependent and must respond to the flow of data from all neighboring local controllers. By means of this principle of interaction, a multiscale system of terminal can be divided into a number of levels. For their coordination should be used a hierarchical structure. In this case, during solution large problem is divided to several private sublevel problems. An example of hierarchical management structure is shown in Figure 1.

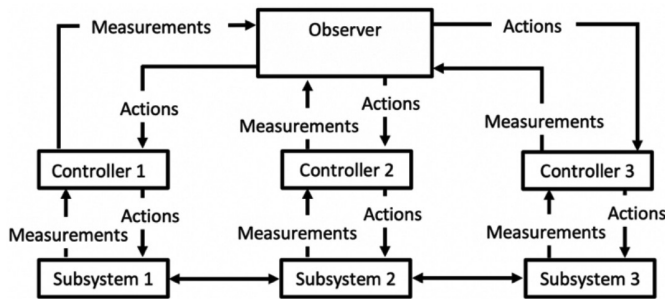


Figure 1. Hierarchical management system

From our point of view, all methods of container terminals managing which are based on software technologies should use only a hierarchical management structure. In contrast to analytical methods, they can use the architecture of combined management in a centralized way with the assessment of the hierarchy of the environment in the definition of agents.

It makes sense to use ship service time as a key performance indicator. This criterion has a strong relation with other performance indicators that directly connected with terminal's transport processes. In general, local performance indicators include: time for calculations; time for service; time to complete the work; the volume of electricity consumption; average and relative AGV travel distance; QC operation; operation of AGV and ASC [19].

4. Hierarchical System of Automated Processes Management

4.1. General Model

General scheme (Figure 2) of a container terminal using hierarchical control system for ship cargo processing is a composition of one QC and several AGVs and ASCs. In standard unloading procedure QC takes container out the ship and puts it to an AGV. Then it goes on with container from berth to the area of container stacking. In this area container processing is done by using ASC. In such a cycle, it is very important to take into account the moment when containers are transferred from one equipment to another.

Management of port terminal processes consists of high- and low-level management and could be characterized by dynamical changes in discrete event time interval and continuous time, which reflects the behavior of a big quantity of terminal facility. To control the dynamical changes of the higher level, the problem of planning is solved according to the minimum time of works completion.

At the lower sublevel hierarchical model of the terminal can be described by differential-algebraic equations. Another higher level, is more complex and description of the system is more notional and should use modeling techniques using

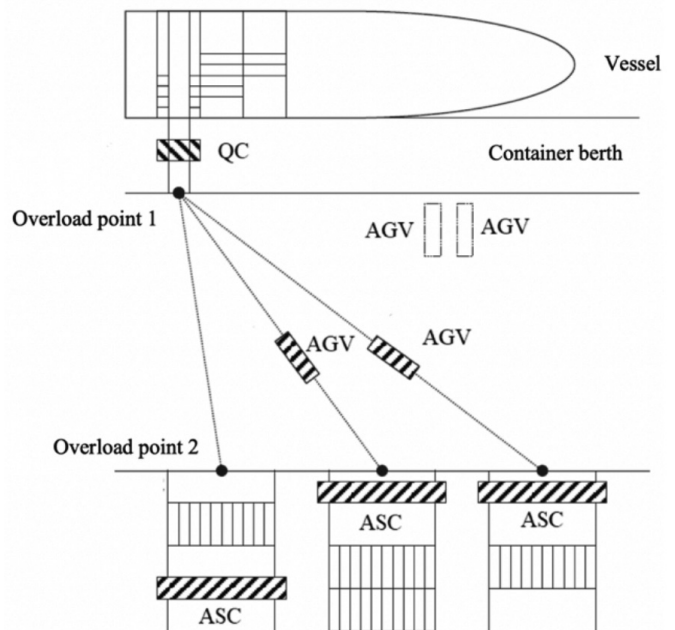


Figure 2. General scheme of a container ship cargo handling

discrete events. Management architecture can be built with decomposition of dynamics of all operations in the system. Typically, the controller assigned to the upper level controls the control group of discrete events, and the lower level controller controls the dynamics of the continuous operation of the equipment. The upper layer and the lower layer interact using a special interface which in real time compile continuous signals and signals of discrete events. The signal of discrete state on the higher level causes dynamical changes of continuous procedure in the lower one [24].

Dynamics of container transportation was modeled at two levels: the dynamics of high-level discrete events (Petri networks, the Max-plus equation); continuous-time dynamics of the lower level (differential equations describing the dynamics of container transporting single facility).

At the system highest level, the behavior was reflected by dynamics of a discrete event. It was reflecting during which period of time and in which sequence the number of containers is processed by the available facility units (e.g. QC, AGV, ASC). The operation of facility elements was presented as a flow on three stages in the form of a discrete system where each work went through several stages. At each stage, a set of the same tasks were used. Each of them was performed sequentially and required a certain amount of time. As it is shown in Figure 3 a work was set as the total process where the container was moved from the ship to the place of containers stacking. Single work was

performed using three types of facility: QC, AGV and ASC. Every operation can be divided into three levels: stage 1 - unloading by QC; stage 2 - moving of single AGV; stage 3 - stacking by ASC use.

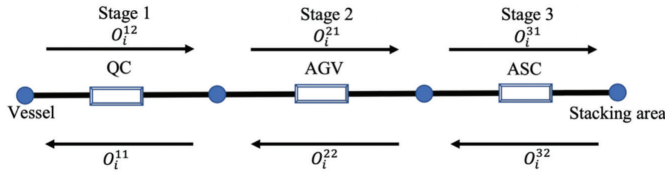


Figure 3. Discrete system of work performance sequence

4.2. Sequences of Equipment Working Places During Ship Processing

To describe the operation with three types of facility shown in Figure 3 should be used: P_i^1 - place of container number i on the ship. P_i^2 - transshipment point where container number i is moved from QC to AGV. P_i^3 - transshipment point where container number i is moved from AGV to ASC. P_i^4 - storage location of container number i .

At the first level, two operations O_i^{11} and O_i^{12} are performed. Operation O_i^{11} is defined as QC movement from P_i^2 to P_i^1 for the i -th container. Operation O_i^{12} is defined as QC movement in the reverse direction with the i -th container. In stage 2, two operations O_i^{21} and O_i^{22} are performed also. During these operations AGV moves from P_i^2 to P_i^3 with the i -th container and returns from P_i^3 to P_i^2 after unloading the corresponding i -th container. Operations O_i^{31} and O_i^{32} are performed on stage 3, where ASC transfers the i -th container from P_i^3 to P_i^4 and returns from P_i^4 to P_i^3 after unloading the i -th container respectively.

The hybrid flow problem for the situation presented in Figure 3 consists in finding sequences of equipment working places that optimally provide processing of the vessel.

We represent N as the number of movements for container transportation from vessel to the stack, F as a set of tasks $|F| = N$. During realization of every operation at each stage, there is a mutual time relation: ending time of the previous stage answers the starting time of the next stage and such time constraints were written in the form:

$$a_i + R(1 - \sigma_{ij}^1) \geq 0, \forall_i \in F, \quad (1)$$

$$a_i + R(1 - \sigma_{ij}^1) \geq b_j, \forall_i \in F, \forall_j \in F, i \neq j, \quad (2)$$

$$a_i + t_i^{11} + t_i^{12} \leq b_i, \forall_i \in F, \quad (3)$$

$$b_j + R(1 - \sigma_{ij}^2) \geq c_i + t_i^{22}, \forall_i \in F, \forall_j \in F, i \neq j, \quad (4)$$

$$b_i + t_i^{21} \leq c_i, \forall_i \in F, \quad (5)$$

$$c_j + R(1 - \sigma_{ij}^3) \geq c_i + t_i^{31} + t_i^{32}, \forall_i \in F, \forall_j \in F, i \neq j. \quad (6)$$

where $\forall_i \in F_1$ and $\forall_j \in F, i \neq j$; $\sigma_{ij}^1 = 1$ describes that the task j is producing exactly after the task i at the 1 stage; $\sigma_{ij}^1 = 0$; $\sigma_{ij}^2 = 1$ describes that the task j is performed immediately after the task i at stage 2; $\sigma_{ij}^2 = 0$; $\sigma_{ij}^3 = 1$ means that the task j is performed immediately after the task i at stage 3, otherwise $\sigma_{ij}^3 = 0$; a_i - starting time of the task i at stage 1, it answers the moment when QC starts moving to P_i^2 ; b_i - beginning of the task i at stage 2, it answers the moment when AGV begins moving to P_i^3 ; c_i - beginning of the task i at stage 3, it answers the moment when ASC starts moving to P_i^4 ; $t_i^{h_1, h_2}$ - execution time of overloading operations $O_i^{h_1, h_2}$, where $h_1 \in \{1, 2, 3\}, h_2 \in \{1, 2\}$; R - constant number.

Inequality (1) demonstrates the opening task performed by QC. Inequality (2) demonstrates relationship between tasks i and j performed by QC. Inequality (3) represents task i done by AGV when QC finished its operation. Inequality (5) demonstrates that task i is performed by ASC when AGV finished its operation. Inequalities (4) and (6) describe the ratio of task i performed by AGV and task j performed by ASC.

In addition to the time limitations in formulas (1)-(6) discrete control variables σ_{ij}^1 , σ_{ij}^2 and σ_{ij}^3 have constraints too. They ensure that each equipment has one previous operation and one subsequent operation for each stage. However, for the first performed operation j and for the last operation i σ_{ij}^1 , σ_{ij}^2 and σ_{ij}^3 ($i \in F, j \in F, i \neq j$) have to take the value 0. Finally, we define two operations 0 and $N + 1$.

With the use of $\Phi_1 = \Phi \cup \{0\}$ and $\Phi_2 = \Phi \cup \{N + 1\}$ we can introduce additional restrictions for the first and last operation. Finally, all restrictions can be written as;

$$\sum_{j \in \Phi_2} \sigma_{ij}^1 = 1, \forall_i \in F, \quad (7)$$

$$\sum_{i \in \Phi_1} \sigma_{ij}^1 = 1, \forall_j \in F, \quad (8)$$

$$\sum_{j \in \Phi} \sigma_{0j}^1 = n_{qc}, \quad (9)$$

$$\sum_{i \in \Phi} \sigma_{i(N+1)}^1 = n_{qc}, \quad (10)$$

$$\sum_{j \in \Phi_2} \sigma_{ij}^2 = 1, \forall_i \in F, \quad (11)$$

$$\sum_{i \in \Phi_1} \sigma_{ij}^2 = 1, \forall_j \in F, \quad (12)$$

$$\sum_{j \in \Phi} \sigma_{0j}^2 = n_{agv}, \quad (13)$$

$$\sum_{i \in \Phi} \sigma_{i(N+1)}^2 = n_{agv}, \quad (14)$$

$$\sum_{j \in \Phi_2} \sigma_{ij}^3 = 1, \forall_i \in F, \quad (15)$$

$$\sum_{i \in \Phi_1} \sigma_{ij}^3 = 1, \forall_j \in F, \quad (16)$$

$$\sum_{j \in \Phi} \sigma_{0j}^3 = n_{asc} \quad (17)$$

$$\sum_{i \in \Phi} \sigma_{i(N+1)}^3 = n_{asc} \quad (18)$$

Equations 7 and 8 show that for each operation $i \in F$ one previous and one subsequent operation would be performed by QC. Equations 9 and 10 reflect the use of n_{qc} . Equations 11 and 12 show that in every operation $i \in F$, there exists only one previous operation and single subsequent operation nominated to a specific AGV. Equations 13 and 14 reflect the use of n_{agv} . Equations 15 and 16 indicate that for every operation $i \in F$ one previous and one subsequent operation would be performed by a certain ASC. Equations 17 and 18 reflect the use of n_{asc} .

It is possible to model the hierarchical dynamics of discrete events for three types of equipment during the unloading of a container ship on the basis of (1-18). In this process, the ending time i at every point and a chain of operations performed by certain equipment at each stage are variable. They are defined exclusively by the system controller only.

A similar system of equations can be used in modeling of ship loading operations. In this case should be varied the order of QC-AGV-ASC to ASC-AGV-QC and replaced t_i^{22} with t_j^{22} in (4). In this case dynamics of continuous operation of individual parts of equipment can be described as

$$\dot{r}(t) = g(r(t), u(t)), \quad (19)$$

$$\dot{r}_1(t) = r_2(t), \quad (20)$$

$$\dot{r}_2(t) = u(t), \quad (21)$$

where $r(t)$ - a continuous status; $u(t)$ - facility control variable; $r_i(t)$ - position of equipment unit, m; $r_2(t) \in [v_{min}, v_{max}]$ - velocity of equipment unit, m/sec; $u(t) \in [u_{min}, u_{max}]$ - acceleration of equipment unit, m/sec².

4.3. Two-Level Structure of the Hierarchical Management System

The structure of the hierarchical container terminal management system can also be described as two-level on a base of proposed method. As one can see in Figure 4, at the top level, the supervisory dispatcher determines the time limits of cargo operations. The stage controller in online mode assigns the value of time interval of every operation to a specific unit of facility. In the proper way to plan operations supervisor have to know the time necessary for each technological operation. Therefore, the upper level requires from hardware dynamics controllers from lower level the value of minimum time needed to perform a certain technological operation. The supervisory dispatcher plans operations and compiles the work schedule on the base of the required time which was received from the controller of the stage.

On a base of the continuous time dynamics and with evaluation of a cost function which was found out over obtained time, the upper level suggests the use of the optimal amount of equipment. When system answering the lower level, it's governed by the dynamics of uninterrupted operation of every individual unit of facility. The controller of lower layer schedules operation of the specified equipment when the value of the time interval for operations from the upper layer is received.

To reduce the consumption volumes of energy, the upper-level controller should provide the maximum level of energy-saving planning. In the case when there is a sufficient time interval, it should maximally increase the duration of all operations [25].

The main aim of the supervisory dispatcher is to achieve the minimum level of energy efficiency. In this case, it is necessary the time schedule for the completion of the n -th number of overload operations reduce to a minimum

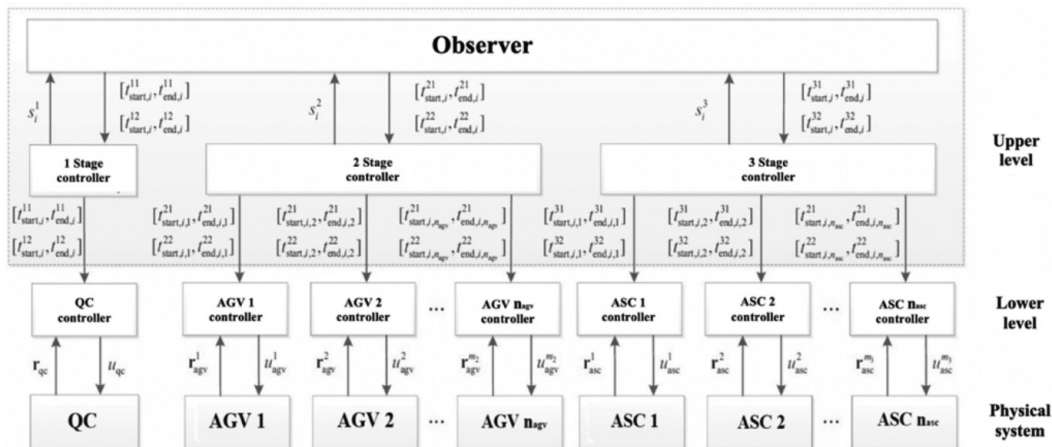


Figure 4. Common structure of the hierarchical management system

with considering the maximum time for all operations completion.

If we name for the same equipment all identical operations O_i^{11} and O_i^{12} as $t_i^{11} = t_i^{12}$, and $t_i^{31} = t_i^{32}$ for operations O_i^{31} and O_i^{32} it is possible to express the total time of all operations as $\|t\|_1$ ($\|\cdot\|_1$ - l-norm). In this case parameter t was written as

$$t = [t_1^{11}, \dots, t_N^{11}, t_1^{12}, \dots, t_N^{12}, t_1^{21}, \dots, t_N^{21}, t_1^{22}, \dots, t_N^{22}, t_1^{31}, \dots, t_N^{31}, t_1^{32}, \dots, t_N^{32}]^T$$

Considering the dynamics of discrete events, the optimization problem was formulated in a form;

$$\max_{t,a,b,c,\sigma} \|t\|_1, \tag{22}$$

It should be solved under conditions;

$$\min_{a,b,c,\sigma} \|w\|_\infty, \tag{23}$$

$$s_i^{h_1, h_2} \leq t_i^{h_1, h_2}, \forall_i \in \Phi, \tag{24}$$

$$t_i^{11} = t_i^{12}, \forall_i \in \Phi, \tag{25}$$

$$t_i^{31} = t_i^{32}, \forall_i \in \Phi, \tag{26}$$

where $s_i^{h_1, h_2}$ is the lower limit of $t_i^{h_1, h_2}$.

The value of lower limit $s_i^{h_1, h_2}$ could be obtained by the stage controller during the calculation of minimum operating time. Thus, to optimize the system, the equality $s_i^{h_1, h_2} = t_i^{h_1, h_2}$, with $\|w\|_\infty = w_{min}$ should be fulfilled. At the same time, in the first stage, σ_{ij}^1 , σ_{ij}^2 and σ_{ij}^3 are used as input data for optimization at the next upper stage.

The highest value of processing time (22) with the minimum overall work schedule can be written using conditions;

$$\|w\|_\infty = w_{min} \tag{27}$$

$$s_i^{h_1, h_2} \leq t_i^{h_1, h_2}, \forall_i \in \Phi \tag{28}$$

$$t_i^{11} = t_i^{12}, \forall_i \in \Phi \tag{29}$$

$$t_i^{31} = t_i^{32}, \forall_i \in \Phi \tag{30}$$

To make analysis easier the two-level structure of the hierarchical control system for three types of equipment with these equations can be divided into two stages:

- The first stage, when the lower limit of working time is stated by the controller at the moment when request from the supervisory dispatcher about the time that is necessary for the technological operation is received;
- The second stage, when supervisor set up the time of technological procedures at every stage. The time limits of all operations at every stage are transmitting from the

dispatcher to the controller which already assigns the work to a specific piece of facility at every stage.

When using these two stages, the following seven procedures should be performed: the supervisor sends a request for the time which is necessary to realize operation at every stage; the minimum duration for each operation using QC, AGV and ASC is found out by the appropriate stage controller; supervisory dispatcher receives data about duration for each operation from stage controller; supervisory dispatcher calculates work (with condition of minimal energy spending) timetable in three stages; supervisory dispatcher sends to controller the data about time necessary to conduct operations; upper-level controller makes an assignment of every operation to a specific unit of equipment at every stage; QC, AGV, and ASC controller (answering to lower-level) receives data about time duration diapason to calculate trajectories of each equipment to receive minimal energy spending.

The whole procedure of the hierarchical structure for terminal management with all stages shown in Figure 5.



Figure 5. Procedure of hierarchical management structure

The analysis of the proposed model makes it possible to conclude that the hierarchical management structure emphasizes the interdependence of the planning task regarding the dynamics of discrete events of all equipment units and the task of optimal control between individual equipment elements with consideration of continuous time dynamics.

5. Results

5.1. Dynamics of Discrete Events in A Hierarchical Control System

To consider the quantity of new containers in the dynamic model of the hierarchical management structure one should use following equations;

$$x(k + 1) = Ax(k) + B_1 u(k) + B_2 \delta(k) + B_3 z(k) + B_4 d(k), \tag{31}$$

$$y(k) = Cx(k) + D_1 u(k) + D_2 \delta(k) + D_3 z(k), \tag{32}$$

$$E_2 \delta(k) + E_3 z(k) \leq E_1 u(k) + E_4 x(k) + E_5, \tag{33}$$

where $d(k)$ is a term indicating the number of new arriving containers, factors B_4, D_4 show how $d(k)$ makes influence on current state and final output.

These three equations give ability to consider delivery of new containers as an external incoming data in combination with position and velocity of machines. Dynamics of machines which is individual for every unit do not change, but the choice of machines actions remains variable.

To provide evaluation of the model for every stage of time it is necessary to specify value of $d(k)$ and for the proposed controller formulate objective function. This function consists of two parts: load capacity and energy efficiency.

We have used completion time and energy consumption as main performance indicators.

Time to complete transportation of all containers, provided that $N_s(k) = N$ and energy consumption of all machines are determined by the equations;

$$k_{finish} = \min k, \quad (34)$$

$$E_{tot} = E_{qc} + E_{agv} + E_{asc}, \quad (35)$$

where E_{tot} is total energy consumption of all technological equipment; E_{qc} , E_{agv} and E_{asc} are QC, AGV, and ASC energy consumption, respectively.

E_{qc} values can be calculated from;

$$E_{qc} = \sum_{k=0}^{N_{sim}-1} E_{qc}(k) \quad (36)$$

$$E_{qc}(k) = \begin{cases} 0.5 m_{qc}^{unload}(k) \times (v_{qc}^2(k+1) - v_{qc}^2(k)) \\ v_{qc}^2(k+1) > v_{qc}^2(k) \end{cases} \quad (37)$$

$$m_{qc} = \begin{cases} m_{qc}^{unload} v_{qc}(k+1) < 0 \\ m_{qc}^{load} v_{qc}(k+1) > 0 \end{cases} \quad (38)$$

where N_{sim} is a simulation length; m_{qc}^{unload} , m_{agv}^{unload} , m_{asc}^{unload} are weights of QC, AGV and ASC without containers; m_{qc}^{load} , m_{agv}^{load} , m_{asc}^{load} are weights of QC, AGV and ASC with container.

To find the correct N_p it's necessary to check effectiveness of the procedure of all containers processing. This can be done when one changes the value of N_p of the proposed controller. In the case when all containers can be processed completely one should use notation "1". In opposite situation, when all containers cannot be transferred to the stacking area one should use notation "0". During modelling we tested different values of N_p with quantity of containers N equals 10.

Figure 6 shows that a short forecasting horizon has no ability to ensure that all containers will be transferred from the ship to the stack location. Short forecasting horizons have no ability to predict full cooperation between all parts of the system. Due to imperfect prediction units of equipment

remain in the same area. That is the main reason why all containers wouldn't be transported to a final stack location with a short forecast horizon.

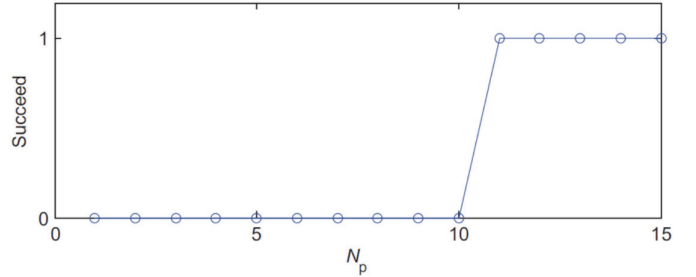


Figure 6. Effect of simulation in relation to the forecast horizon N_p

5.2. Capacity and Energy Efficiency of Container Terminals Under a Hierarchical Management System

Simulation was done for the general pier scheme shown in Figure 7 in order to determine efficiency indicators.

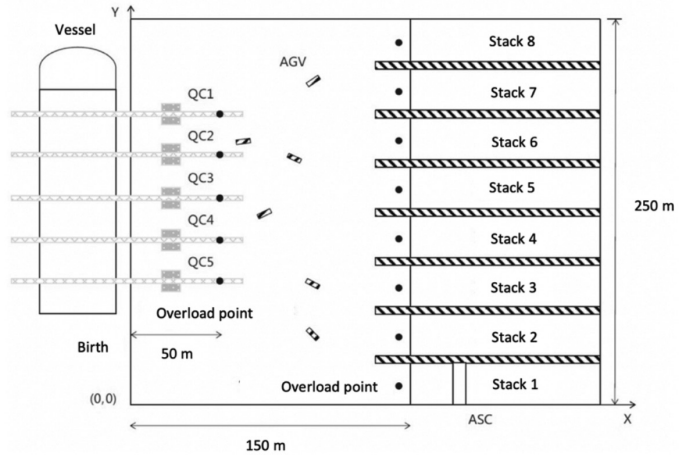


Figure 7. Scheme of the pier for unloading process

Figure 8 reflects energy consumption at the minimum completion time for operation and at the optimal energy consumption. In each test, the time of single technological operation of every individual unit of equipment was stated. It was assumed that each piece of equipment worked at maximum speed. The results show that in energy-saving mode, every production equipment does not need to run at maximum speed. Comparison of different power consumption on the graph shows that the maximum energy saving was 37%.

Figures 9 and 10 show traditional and energy-saving graphs when using a hierarchical control system. The number in every block is answering to the serial marking of the unloaded container. In a regular target time of single operation per unit of facility was fixed. Because of necessity

to synchronize different types of technological facility, some devices had a longer waiting time. This can be seen in the graph of AGV and ASC in Figure 9. As one can see in Figure 10 equipment has a more flexible processing time and that is a main reason why time period required to realize an operation by one facility unit can be increased. This fact for energy reduction is beneficial. Reduction of spent energy didn't lead to arising of time necessary to complete operation & As it can be seen in Figures 9 and 10 completion time is fully identical.

6. Discussion

Hierarchical management system for container vessels automated cargo handling, which has been developed during research works has one important advantage. On the lower level the hierarchical model of the system can be described with the use of fairly simple differential-algebraic equations but on a higher level it is based on the use of unique method for modeling discrete processes. High quality management architecture can be created on the base of the process when dynamics of all technological operations in the system of container terminal is divided onto detailed component

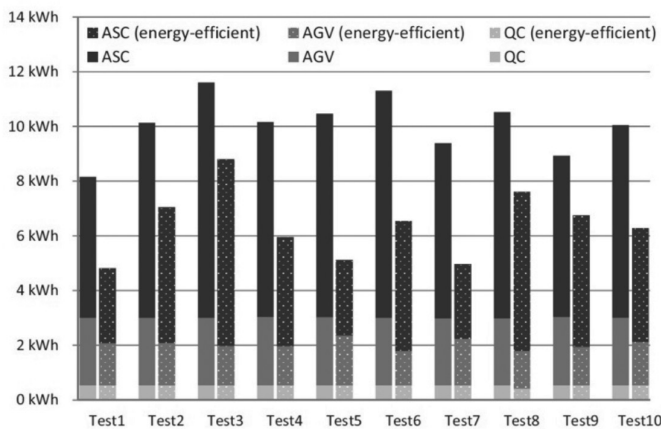


Figure 8. Energy consumption

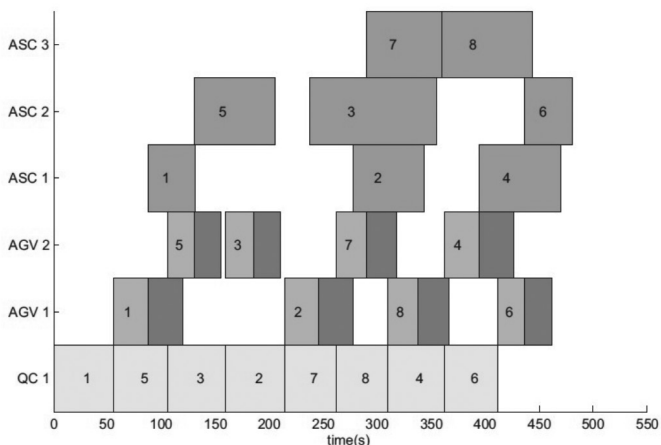


Figure 9. Schedule of the usual hierarchical management system

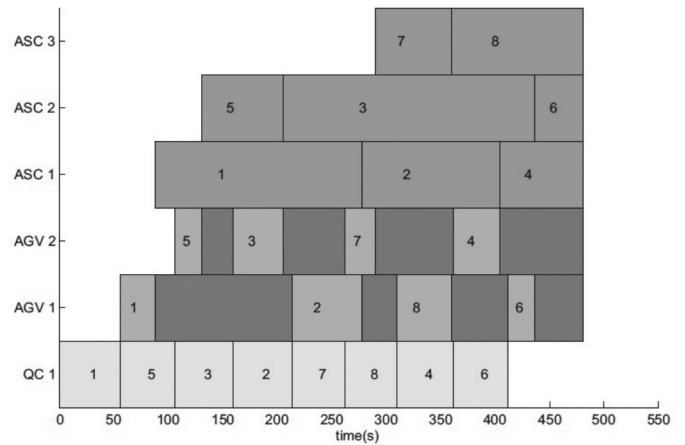


Figure 10. Energy-saving graph of the hierarchical control system

hierarchical levels. In the future this type management will be characterized by maximum efficiency, low levels of accumulated energy and improved safety indicators.

At the same time, it can be stated that all current researches should be directed to the development of new concepts and methods that give an ability to optimize the management of automated processes of overloading operations during processing of container vessels. From our point of view, new methods should use algorithms, which during operation of the terminal will be using artificial intelligence.

Main basis for introduction of artificial intelligence inside port terminal management can be algorithms that are stated on the control system which is a hierarchical and described in this article. However, in the future, such algorithms will require a huge amount of accumulated statistical results from the operation of all port terminals in the previous time. It is possible to state, that such statistical data would be containing not only operational technical parameters of local areas of terminal. Such data can, for example, provide precise meteorological indicators that can determine the influence of wind drag force on the speed of unloading containers or the change in energy consumption due to the ambient temperature.

The use of artificial intelligence based on hierarchical control systems will make it possible to change significantly the vessel's stand by hours by increasing the speed of vessel processing and improve the level of safety during the operational hours of container terminals. This optimization is especially important in situations where takes place a constant change in used operating equipment during the processing of a large number of containers.

7. Conclusion

The dynamics of container transportation in port terminal should be thought-out as a hierarchical system which

includes the dynamics of permanent time and individual events. A hierarchical management structure for this system was offered and it contains two interconnected levels. The upper level dedicated during operation for scheduling. At this level time for operation of every unit of facility is stated and minimum time for operation completing is set. The next bottom level consists of a controller which works with every unit of technological facility. At a lower level could be achieved reduction in energy consumption and it could be done by meeting time constraints given by the upper level.

The hierarchical management structure emphasizes the interdependence of the planning task regarding the dynamics of discrete events of all equipment units and the task of optimal control between individual equipment elements taking into account the dynamics of continuous time.

In comparison with traditional container terminal scheduling during simulation was found out that, with the analogical minimum time to complete the process, an optimal approach can save 37% of energy used for its realization.

Authorship Contributions

Concept design: L. L. Nikolaieva, Data Collection or Processing: L. L. Nikolaieva, T. Y. Omelchenko, and O. V. Haichenia, Analysis or Interpretation: L. L. Nikolaieva, and T. Y. Omelchenko, Literature Review: L. L. Nikolaieva, T. Y. Omelchenko, and O. V. Haichenia, Writing, Reviewing and Editing: L. L. Nikolaieva, T. Y. Omelchenko, and O. V. Haichenia.

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