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MULTI-STREAM PROCESS MODELING

Multi-stream processes modeling is carried out on the example of a container ship loading system modeling during maritime transportation. The relevance of the study is determined by the need to improve the safety and operational efficiency of maritime transportation. Traditional cargo placement planning systems are sequential and unable to effectively manage the continuous loading process in real time. The aim of the work is to develop a model of container ship loading as a multi-stream system that ensures synchronization of physical, logistical and engineering operations.

Loading a ship is a continuous process that involves waiting, reconfiguring equipment, and moving cargo. Unforeseen events occur in real-world conditions. Time-phased scheduling allows for minimizing downtime and optimizing the sequence of port resource use, which directly impacts operating costs. Temporal decomposition allows for the creation of an adaptive model that can quickly change the loading plan for subsequent time intervals, minimizing the impact of disruptions.

The concept of a multi-stream approach, within which four integrated flows (physical, logistical, engineering, and management) are distinguished, is substantiated and formalized in the article. The innovative value of the model lies in the transition from sequential verification to integrated multithreading: the management flow uses software synchronization mechanisms (semaphores, locking) to ensure the atomicity of critical operations and dynamic verification of all constraints simultaneously.

A multi-criteria optimization objective function is proposed that minimizes the weighted sum of three key indicators: total vessel downtime, number of unnecessary container rearrangements and ship stability correction costs. The use of heuristic algorithms and graph theory to find optimal indicators is justified.

The practical value of the model is in minimizing the impact of the human factor, increasing vessel safety and reducing port downtime through integrated and synchronized loading process management.

Key words: *cargo placement planning, multi-stream system, multi-criteria optimization, heuristic algorithms, software synchronization, atomicity.*

Introduction. The container ship loading problem is a prime example of a multi-criteria optimization problem with diametrically opposed requirements. The relevance of the research topic is determined by a number of interconnected global economic, technological and environmental factors, the dominant among which is the critical requirement of ship and cargo safety. Effectively managing such a multidimensional task is difficult, and violation of strict loading rules due to the influence of the human factor is unacceptable. Therefore, powerful computer models with a number of means of controlling the synchronization of the streams work are needed. Consideration of the loading problem as a multi-stream system, which allows simultaneous optimization of cargo, port and ship constraints is proposed in the article.

The problem of cargo placement planning is traditionally considered in operations research as a variant of the 3D-Packing Problem. However, classical heuristic decision support systems, as indicated in [1], often work according to the sequential principle: first logistical placement, then engineering verification. This approach does not allow for effective real-time system management and leads to iterative adjustments.

A number of works by well-known authors are devoted to the study of modeling problems related to maritime logistics.

The cargo-mix problem aims at selecting the amount of containers of a given type to load on a vessel is considered in paper [5]. This paper proposes an extended definition that includes the analysis of a circular route with draft restrictions, limitations on expected cargo and the use of a block stowage strategy. A compact formulation of the problem based on the state-of-the-art heuristic decomposition is shown not to be able to solve the extended problem, thus a mathematical approach is presented by authors that can achieve high quality results in a matter of seconds [5].

The work [6] is devoted to the container stowage planning problem (CSPP), a complex optimization problem in maritime logistics aimed at efficiently stowage of containers on ships, balancing revenue, stability, safety and minimizing costly container movement (overloading). The authors emphasize the complexity of modeling large ships with real-world constraints.

Optimization of container ship and depot operations is proposed in [7]. The authors show that even the abstract formulation of container placement planning on container ships is intractable.

Modern research on maritime logistics [2] confirms the need to use multi-criteria optimization to simultaneously consider economic factors (minimizing downtime) and engineering factors (optimal trim for fuel economy). Fundamental constraints related to the technical requirements for container placement and lashing [4] are the rigid basis of any model.

The innovative value of the proposed model is in the transition from sequential verification to integrated multithreading. The model offers a problem solution by using software synchronization mechanisms to ensure atomicity of operations and dynamic verification of all constraints simultaneously.

Main part. The efficient loading/unloading process of a container ship is a complex synchronized work that involves the interaction of physical objects (containers, crane), information systems (cargo data, plan) and engineering requirements (ship stability).

In the context of a multi-stream system, there are four main streams that need to be synchronized and optimized. Let's number them from one to four.

Stream I includes cranes and equipment that are responsible for the direct movement of containers. The speed and consistency of their operation is the basis for the formation of the total vessel downtime.

When modeling container operations, which include moving containers using port cranes and moving them between stacks at the terminal and berth using port equipment, they must also be considered as distributed units, separate streams, and software tools must be provided to synchronize the work. It is worth clearly distinguishing the functions of equipment, as they form separate mini-streams within Stream I.

We define cranes as a key element that determines the overall port performance. The productivity of each crane can be characterized by the number of its movements per hour or by the number of containers moved per hour.

Intra-port equipment includes vehicles for moving containers around the quay: horizontal (for moving from one place to another, for example, trucks for delivering containers from a warehouse) and vertical for stacking containers. The efficiency of Stream I depends largely on the quality of interaction in the exchange zone between horizontal transport (bringing containers) and cranes. If the horizontal stream is not fast enough, the crane is idle, which directly increases the ship's downtime. Ideally, containers should arrive at the quay just in time to minimize buffering and waiting, which requires precise synchronization.

It is necessary to provide technical limitations of the cranes that affect the simulation. This includes, first of all, limitations on the crane's operating area, in particular, limitations on reach, lifting height and speed. To avoid mutual blocking of cranes by each other, models should take into account the need for a safe distance between cranes operating on the same ship, limiting their distribution and speed.

The main optimization aim of modeling the operation of these distributed elements of Stream I is to minimize the time spent on performing operations to install a container on a ship. Special attention is paid to the efficiency of the exchange zone between land transport and the crane. This is achieved by optimally distributing the cranes on the ship, avoiding their mutual blocking and minimizing horizontal and vertical movements of containers at the terminal and the ship.

In the general model, the operating time of the cranes must also be synchronized with the loading sequence determined by the balance system, which we will denote hereafter as Stream III.

The next stream (Stream II) is for planning and management of container units. This stream is responsible for port logistics and cargo restrictions. We can call it the logistics stream.

Port logistics functions include managing the order of unloading/loading according to the ports of destination (for ports that will be first in the ship's route, containers are shipped last). This is the most important limitation. Containers destined for early ports of discharge should be placed above or at least not below containers destined for later ports. This avoids blocking and minimizes double movements. The order of ports of call in the model is the main input for this stream.

Cargo restrictions concern the type of cargo (explosive, flammable, refrigerated, etc.), its weight (the heaviest are placed lower to ensure the stability of the vessel) and dimensions. There are international regulations that strictly regulate the segregation distances between different classes of dangerous cargo. We also take into account that refrigerated containers can only be placed in slots equipped with sockets, which is a strict restriction on location. Stream modeling should include a compatibility matrix.

Stream II logistics also includes internal terminal logistics (where and in what order containers are stored on the site for loading).

The target task of Stream II modeling is to minimize the occurrence of double moves, where containers have to be moved to another location to ensure the correct location of the containers (for example, heavy containers at the bottom, light containers at the top, hazardous cargo in isolation). Minimization is not only a logistical target task, but also a direct financial target task, as each extra container move costs the operator time and money (through using crane and personnel).

This stream provides strict logistical constraints for Stream I that cannot be violated, regardless of the desired speed of crane operations.

Stream III simulates the operation of the ship's balance system and is an engineering stream. Its task is to ensure constant monitoring and prediction of violations (exceeding permissible norms) of the ship's stability (center height), its heel and trim after each simulated container movement. This also includes control over hard physical constraints, including local loading on individual stacks and the maximum permissible draft of the ship.

This stream monitors hard physical constraints that must be taken into account at the placement planning stage, i.e. before the start of crane operations.

The key task of Stream III modeling is to minimize deviations from ideal stability parameters, which is a safety priority. The easiest way to do this is through a ballast system (pumping water for leveling), but this entails additional time and energy costs (which are taken into account as a penalty in the objective function). Therefore, the main strategy is to optimize the loading plan with a uniform distribution of weight over the entire plane.

At the end of the loading operations, it is necessary to reach an optimized trim, which will provide less water resistance and fuel economy during the movement of the ship after leaving the port.

Stream IV includes the control and information system. It is the integrating core of multi-streaming and is responsible for synchronizing all data between the ground (port) infrastructure terminal management system and the placement planning module. It is responsible for collecting and processing standardized messages (complete information about the location of each container on the ship), generating and transmitting commands to cranes, and monitoring the ship's condition in real time using the stability and strength computing module.

The key task is to ensure the reliability and efficiency of information, which is the basis for decision-making and allows the system to respond quickly to unforeseen events (for example, cargo delay or discrepancy in actual weight).

The control system will be the core of multi-threading, ensuring the execution of the plan generated by the optimization model and feedback for correction. It monitors and verifies the current ship parameters after each loading step.

Successful container ship loading simulation requires that the optimization algorithm operate not sequentially but simultaneously (multi-threaded), integrating the tight constraints of Streams II and III with the time requirements of Stream I, and guided by data from Stream IV.

The need to include software synchronization tools is critical to the transition from «planning» to «real-time multi-stream system management».

Synchronization mechanisms (semaphores and monitors) are used to control access of different threads (e.g. cranes) to shared resources, such as data on free slots or ship stability. This prevents a «data race» when two cranes try to occupy the same slot on the deck at the same time.

Locks ensure the integrity of the layout plan during its dynamic updates. For example, when a container is loaded, its slot is locked until the balance system confirms the new stability state of the ship within normal limits.

The use of parallel programming will ensure simultaneous calculation of the optimal placement of the next batch of cargo, prediction of stability parameters, and generation of commands for crane operation.

The function of Stream IV is to ensure the atomicity (indivisibility) of critical operations. That is, the container movement operation must be completed and confirmed by all systems (I, II, III – physical, logistics and engineering streams) before the next operation begins.

The analysis of key optimization problems (minimizing operation time, unnecessary rearrangements, and costs for correcting engineering parameters) fits perfectly into the classic multi-criteria model of minimizing total weighted costs.

The objective function min C_{total} should minimize the total costs, which are the sum of the three weighted criteria representing our Streams (I, II, III).

The objective function of minimizing the total weighted costs has the form:

$$\min C_{total} = W_1 \times T_{total} + W_2 \times M_{restow} + W_3 \times C_{ballast}, \quad (1)$$

where C_{total} – total weighted costs/fines; W_1, W_2, W_3 – weighting factors (priorities) reflecting the relative importance of the criteria.

Each component details a separate aspect.

T_{total} defines the total time (total ship idle time) spent on all crane operations (loading and unloading) in the current port. It is defined as the total time spent loading containers and the time spent on ballast system operation (time spent pumping water to correct heel/trim), which is a direct increase in ship idle time.

M_{restow} – the number of containers that will have to be temporarily unloaded at the terminal (or rearranged on the ship) to gain access to the cargo destined for the current port. Minimizing M_{restow} is key to ensuring the logistics stream efficiency.

The cost of correction $C_{ballast}$ is the cost (e.g. penalty) associated with the need to operate the ballast system. This may include the cost of electricity for pumps, wear and tear on the equipment, and the environmental penalty (if applicable).

Thus, the objective function is to find the optimal balance between speed (min T_{total}), logistical efficiency (min M_{restow}) and engineering safety and economy (min $C_{ballast}$).

This formalization allows us to simultaneously take into account economic efficiency (criteria 1, 2) and engineering safety (criterion 3), which fully corresponds to the concept of multi-criteria optimization of a multi-stream system.

Since the container ship loading problem is multi-criteria, hypercomplex, and combinatorial in nature (a large number of possible solutions), we cannot effectively solve it using only classical mathematical programming methods.

For a complete initialization of the multi-criteria optimization model, let`s specify a clear list of input variables (state parameters) grouped by main objects. These variables reflect the current state of the system before the start of loading and are the initial data for the algorithm.

1. Variables describing the logistical and physical characteristics of each individual container:

ID_k: unique identifier of the k-th container;

P_DEST_k: container destination port (key logistical constraint of Stream II).

VG_k: actual container weight in tons;

T_TYPE_k: container type (20ft, 40ft, etc.);

C_CLASS_k: dangerous goods class (IMO Class), if applicable (for compatibility/segregation testing).

R_REQ_k: binary variable indicating whether refrigerated power is required (1 – yes, 0 – no);

$P\_LOG\_INIT_k$: initial location of the container at the terminal (for calculating ground transport travel time in Stream I).

2. <u>Variables describing the physical and operational limitations of cranes (Stream I):</u>

N_{crane}: total number of cranes for operation on the ship;

V_{lift_i}: maximum vertical lifting/lowering speed of the crane *i* (meters per second);

V_{trav_i}: maximum speed of horizontal movement of the crane along the quay (meters per second);

R_{max_i}: maximum crane boom reach (working area);

D_{save}: minimum permissible safe distance between two cranes operating on the ship (to avoid blocking);

T_{cycle_i}: average crane operating cycle time (minute/container) including lifting/lowering.

3. <u>Variables describing the current physical state and available resources of the ship:</u>

N_{slots}: total number of available slots for placing containers on the ship;

M_{dim}: dimensional matrix of the ship (bay, row, tier) for determining coordinates;

R_{slots}: binary matrix (or list) of slots equipped with sockets for reefer containers;

$L_{max}(x,y)$: maximum allowable stack load limit in the coordinate (x,y);

P_{PORTS}: sequence of ship ports of call (key logistics parameter);

D_{init}: initial draft of the ship before loading;

D_{max}: the maximum permissible draft of the ship;

L_{ship}: current center of ship gravity (longitudinal coordinate L_{CG});

T_{ship}: the current center of ship gravity (lateral coordinate T_{CG});

V_{ship}: the ship's current metacentric height (GM), a key indicator of stability.

4. <u>Variables describing stability correction capabilities and associated costs:</u>

V_{pump}: ballast water pumping rate (m^3/h);

T_{pump_min}: minimum time required to activate and complete the ballast operation cycle;

$C_{ballast\_unit}$: cost/penalty per unit of time of the ballast system operation (e.g., monetary unit/min);

Q_{tank}: current volume of water in each ballast tank.

Let`s detail the impact of key variables on the optimization streams (Stream I, Stream II, Stream III). This will help to better understand how the input data is used by the objective function min C_{total} to synchronize the system.

Stream I focuses on speed and efficiency of crane operations to minimize overall ship downtime (T_{total}).

Both variables (V_{lift_i} and V_{trav_i}) directly affect the time it takes for a container to move from the terminal to the slot. The algorithm uses these speeds to calculate the expected loading time T_{load}, which is part of T_{total}.

Variable D_{safe} (safe distance) sets spatial constraints for the distribution of cranes (N_{crane}) on the ship. The optimization should find a distribution of taps that maximizes parallelism but avoids deadlock, preventing downtime (increasing T_{total}).

Variable $P\_LOG\_INIT_k$ (initial location) affects the efficiency of the exchange zone between ground transport and the crane. The closer the container is to the crane's work zone, the shorter the waiting time (decrease in T_{total}).

Stream II is responsible for the correct placement of cargo according to safety requirements and unloading sequence to minimize unnecessary rearrangements (M_{restow}).

Variable P_{PORT} (port sequence) imposes a top-down constraint. A container with a later destination port must be placed below containers for earlier ports. Violation of this rule leads to the growth of M_{restow}.

Variable C_CLASS_k (hazard class) sets strict segregation (distance) constraints between incompatible cargo classes. Optimization must find a location that satisfies all compatibility requirements to avoid the need to rearrange M_{restow} later.

Variable R_{slots} (slots with sockets) sets a strict positional restriction for reefer containers ($R\_REQ_k = 1$). The algorithm can only consider slots with sockets to prevent logistics disruption.

Stream III controls the stability, roll and trim of the shiop, minimizing correction costs ($C_{ballast}$).

Variable VG_k (container weight) is used to optimize placement (heavy containers at the bottom and closer to the ship's axis) to ensure maximum stability (GM) and reduce heel, minimizing the need for $C_{ballast}$.

Variables L_{ship}, T_{ship}, V_{ship} (current center of gravity) are used for dynamic verification. After each simulated loading step, the system calculates a new center of gravity. If the new parameters are outside the acceptable limits, the algorithm either rejects the step or imposes a penalty ($C_{ballast}$) for activating the ballast system.

Variable $L_{max}(x, y)$ (local load) sets a strict limit on the total weight in a single stack. This prevents structural damage and is also a safety measure.

Variables V_{pump} and $C_{ballast\_unit}$ (speed and ballast cost) determine the size of the penalty. The higher the cost ($C_{ballast\_unit}$), the higher the priority given to optimization solutions that avoid the use of a ballast system, even if this may slightly increase T_{total} or M_{restow} (the influence of weighting factors W_1, W_2, W_3).

Thus, all these variables serve as constraints and coefficients within the multi-criteria model, where Stream IV (management) synchronizes their dynamic verification.

Time relationships describe the dependence of the total downtime (T_{total}) on the duration of individual operations:

$$T_{total} = T_{load} + T_{ballast}, \quad (2)$$

where T_{load} – total loading time, which depends on the speed and number of cranes, their work cycles, and the efficiency of the exchange area. The mathematical relationship here consists of the sum of the cycle times of all cranes operating in parallel, taking into account speed limits (V_{lift}, V_{trav}) and safe distance (D_{safe}); $T_{ballast}$ is the time for stability correction. It depends on the required volume of water pumped and the performance of the pumps (V_{pump}).

The engineering relationships of Stream III describe the dependence of the stability and ship`s stability on the placement of cargo. They are the basis for calculating ballast cost ($C_{ballast}$), which depend on the degree of deviation of engineering parameters (list, trim, metacentric height V_{ship}) from ideal values. The center of gravity of the ship depends on the weight of each container and its specific coordinates of placement on the ship.

The new position of the ship's center of gravity (or object) is calculated as a weighted average of all weights on the ship. For simplicity, this is considered as the movement of the center of gravity (CG_{Shift}).

If the ship has an initial weight W_{init} and an initial center of gravity CG_{init}, and a container with a weight VG_k is installed on it in the coordinate r_k, then the new position of the center of gravity is determined by the formula (3):

$$CG_{new} = \frac{W_{init} \cdot CG_{init} + VG_k \cdot r_k}{W_{init} + VG_k}, \quad (3)$$

where CG_{new} – new position of the ship's center of gravity after loading the container. This is a vector that has three components: longitudinal (L), transverse (T) and vertical (V) coordinates: $CG_{new} = (L_{CG,new}, T_{CG,new}, V_{CG,new})$; W_{init} – initial weight of the ship (including cargo, fuel, stores, etc.); CG_{init} – the initial ship's center of gravity (its coordinates); VG_k – weight of the container to be installed; r_k – coordinates of the gravity center of the container being installed ($r_k = (L_k, T_k, V_k)$); $W_{init} + VG_k$ – new gross weight of the ship.

Formula (3) is applied separately for each axis (longitudinal, transverse and vertical) to ensure full engineering control (Stream III):

1. Longitudinal coordinate (*L*), affects trim:

$$L_{CG,new} = \frac{W_{init} \cdot L_{CG,init} + VG_k \cdot L_k}{W_{init} + VG_k}. \quad (4)$$

2. Transverse coordinate (*T*), affects roll:

$$T_{CG,new} = \frac{W_{init} \cdot T_{CG,init} + VG_k \cdot T_k}{W_{init} + VG_k}. \quad (5)$$

3. Vertical coordinate (*V*), affects stability (metacentric height):

$$V_{CG,new} = \frac{W_{init} \cdot V_{CG,init} + VG_k \cdot V_k}{W_{init} + VG_k}. \quad (6)$$

This dynamic variable $V_{CG,new}$ is critical because it determines the new stability index of the ship. If it goes beyond the norm, it leads to additional costs $C_{ballast}$.

The formula for the dependence of ballast costs ($C_{ballast}$) on the degree of engineering parameters deviation is given as a proportional dependence. In a full mathematical model, this dependence can be formalized as a specific penalty coefficient: the greater the violation of engineering norms, the greater the cost (penalty).

The cost of correcting $C_{ballast}$ is determined as the sum of two main components: operating costs (time penalty) and the penalty for exceeding the permissible engineering limits:

$$C_{ballast} = T_{ballast} \cdot C_{ballast,unit} + P_{penalty}. \quad (7)$$

Operating costs (time penalty) associated with the need to activate the ballast system, which increases the ship's downtime T_{total}:

$$T_{ballast} = \sum_j \frac{\Delta v_j}{v_{pump}} + T_{cycle,adjust}, \quad (8)$$

where: $T_{ballast}$ – total time spent pumping ballast (added to T_{total}); $C_{ballast,unit}$ – cost/penalty per unit of time of the ballast system operation (e.g. $/min); ΔV_j – required volume of ballast pumping in the tank *j* (m³); V_{pump} – pump performance (m³/ min); $T_{cycle,adjust}$ – additional time, that takes into account continuous operations (e.g., time to open/close valves).

The penalty for exceeding the permissible limits that the algorithm imposes on the solution, which leads to a critical deviation of the engineering parameters, can be calculated by the formula:

$$P_{penalty} = W_{penalty} - (\max(0, |Kren| - Kren_{max}) + \max(0, |Dif| - Dif_{max})) \quad (9)$$

where $W_{penalty}$ – high weighting coefficient (penalty factor) reflecting the priority of safety (for example, $W_{penalty}$ significantly exceeds W_1, W_2, W_3); *Kren* – absolute value of the current ship's roll (lateral tilt); $Kren_{max}$ – maximum allowable roll (hard limit); Dif – absolute value of the current trim (bow/stern tilt); Dif_{max} – maximum allowable trim.

The function max(0, x) ensures that the penalty is only charged when the deviation x is positive (i.e. exceeds the allowable limit).

Thus, $C_{ballast}$ in the objective function is the cumulative cost of ballast activation (increase in T_{total}) and an additional penalty if even after simulated loading and/or correction the parameters are still unacceptable.

The local load L_{max} is expressed as a hard constraint-inequality: the sum of the weights of containers in a particular stack must not exceed the maximum allowable load L_{max}.

The mathematical relationships for Stream II logistic constraints (for example, for M_{restow} or segregation requirements C_{CLASS}) are usually expressed not as formulas, but as Boolean (logical) constraint functions or compatibility matrices that the algorithm must check at each step.

A model that considers the system as multi-threaded usually requires the use of heuristic and meta-heuristic algorithms to find suboptimal solutions in an acceptable time. We can rely on any algorithm from the main group, which includes genetic algorithms, simulated annealing, ant colonies, heuristic priority rules. It is better to combine them, where one algorithm searches for a feasible solution and the other tries to improve it. It is also advisable to conduct several experimental runs of the algorithms and choose the best of the resulting solutions.

It is advisable and useful to use graph theory. It provides an ideal mathematical apparatus for visualizing and analyzing the relationships between elements of a multi-stream system. Graph theory is a formalization framework for the multi-stream model. It makes rigid logistical and physical constraints measurable and algorithmically processable.

Conclusions. The concept of a multi-stream system for modeling the container ship loading problem is substantiated and formalized in the work. Four streams (physical, logistical, engineering and management) are isolated and characterized. They provide comprehensive integration. The proposed model provides software synchronization and atomicity of critical operations. This allows minimizing the impact of the human factor, increasing ship's safety, and reducing port downtime due to dynamic verification of engineering parameters in real time.

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МОДЕЛЮВАННЯ БАГАТОПОТОКОВИХ ПРОЦЕСІВ

Моделювання багатопотокових процесів здійснюється на прикладі моделювання системи завантаження контейнеровоза під час морських перевезень. Актуальність дослідження визначається необхідністю підвищення безпеки та операційної ефективності морських перевезень. Традиційні системи планування розміщення вантажу є послідовними та нездатні ефективно управляти неперервним процесом завантаження у реальному часі. Метою роботи є розробка моделі завантаження контейнеровоза як багатопотокової системи, що забезпечує синхронізацію фізичних, логістичних та інженерних операцій.

Завантаження судна – це неперервний процес, що включає очікування, переналаштування обладнання та переміщення вантажу. У реальних умовах виникають непередбачені події. Розбиття на часові етапи дозволяє мінімізувати час простою та оптимізувати послідовність використання портових ресурсів, що прямо впливає на операційні витрати. Темпоральна декомпозиція дозволяє створити адаптивну модель, яка може швидко змінити план завантаження для наступних часових інтервалів, мінімізуючи вплив збоїв.

У статті обґрунтовано та формалізовано концепцію багатопотокового підходу, в рамках якої виділено чотири інтегровані потоки (фізичний, логістичний, інженерний та управлінський). Інноваційна цінність моделі полягає у переході від послідовної перевірки до інтегрованої багатопотоковості: управлінський потік використовує механізми програмної синхронізації (семафори, блокування) для забезпечення атомарності критичних операцій та динамічної верифікації усіх обмежень одночасно.

Запропоновано цільову функцію багатокритеріальної оптимізації, яка мінімізує зважену суму трьох ключових показників: сумарний час простою судна, кількість зайвих перестановок контейнерів та витрати на корекцію остійності. Обґрунтовано використання евристичних алгоритмів та теорії графів для знаходження оптимальних показників.

Практична цінність моделі полягає у мінімізації впливу людського фактору, підвищенні безпеки судна та скороченні часу простою в порту за рахунок інтегрованого та синхронізованого управління процесом завантаження.

Ключові слова: *планування розміщення вантажу, багатопотокова система, багатокритеріальна оптимізація, евристичні алгоритми, програмна синхронізація, атомарність*.

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