Досліджується задача обґрунтування структури парку портового перевантажувального обладнання. Побудована та проаналізована паретова межа відповідної задачі багатокритеріальної оптимізації. Запропоновано методику, що дозволяє зробити обґрунтований вибір оптимальної структури парку перевантажувальних машин. Отримана структура забезпечує баланс між економічними показниками роботи порту і тривалістю стоянки суден

Ключові слова: портове перевантажувальне обладнання, багатокритеріальне оцінювання, межа Парето, мобільне устаткування

Исследуется задача обоснования структуры парка портового перегрузочного оборудования. Построена и проанализирована паретова граница соответствующей задачи многокритериальной оптимизации. Предложена методика, которая позволяет сделать обоснованный выбор оптимальной структуры парка перегрузочных машин. Полученная структура обеспечивает баланс между экономическими показателями работы порта и стояночным временем судов

Ключевые слова: портовое перегрузочное оборудование, многокритериальное оценивание, граница Парето, мобильное оборудование

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SUBSTANTIATION OF STRUCTURE OF THE PORT HANDLING EQUIPMENT FLEET BASED ON A MULTICRITERIA APPROACH

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1. Introduction

A significant part of handling equipment of Ukrainian ports has reached at present a critical level of wear and requires replacement. Solution of this problem, urgent for the port industry, is associated above all with the rational selection of machinery that best meets the needs of port production. In turn, in order to substantiate the structure of the port machinery fleet, each particular case requires a differentiated approach and appropriate evaluation methods. In this regard, it is of practical interest to develop quantitative methods that allow making balanced decisions, taking into account interests of all participants of the port services market.

2. Literature review and problem statement

Paper [1] presents a procedure for assessment of operation performance of separate port services. It is based on the use of the concept of a port services chain, taking into account relationships between its elements – port's services. It is shown that vessels' service efficiency in the port increases considerably if there is a developed system of interaction and cooperation between them. However, relationships in the system "port – ship owners – cargo owners" have not been sufficiently studied.

In article [2], a multistage model for evaluation of internal and external factors, exerting an impact on the efficiency of port operations, was proposed. In the article, internal factors include the management system, the infrastructure and port services. External factors include transport policy, macroeconomic conditions, and some other factors. Along with this, the paper does not take into account such factors as state of the market for transport services, interaction with strategic partners and consumers of services, provided by the port.

Paper [3] considered the problems of improvement of operation effectiveness of shipping companies under favorable conditions of transport services market, as well as the problems of providing their sustainability under conditions of a crisis. In study [4], a procedure for the substantiation of dynamic indicators of critical loading of vessels was developed. However, all the issues, considered in [3, 4], focus mainly on commercial interests of shipowners. But the needs of other participants of transport services market are not taken into account; in addition, the role of a port and quality of its services in providing effectiveness of fleet operation are underestimated.

Study [5] uses the methods of the mass service theory and the methods of fuzzy logic for the optimization of the infrastructure of port facilities and assessment of vessels' berthing in the port. In the study, a port is considered as a system of mass service with allocation of Erlang probabilities with service discipline that take into account priorities of incoming queries. It should be noted that the structure of distribution of production capacity, presented in [5], reflects only one of the possible particular cases. It does not take into account specificity of work of terminals with a mixed structure of handling equipment fleet and various configuration of the berthage. In addition, the discipline of vessels' service and allocation of probabilities of incoming queries may vary.

Consequences of possible mistakes in planning and mismanagement in the development of ports were discussed in paper [6]. This paper deals with the conflict of interests between the ports' management and local authorities when making joint investment decisions. This work is devoted to critical analysis of inefficient relationships in the system "port – ship owners – cargo owners", which can lead to negative consequences for all participants engaged in these relationships. However, the study does not pay enough attention to issues of formalization of participants' interests and development of mathematical models, within which it would be possible to find an optimal solution of this problem.

In article [7], the influence of various factors on the change in magnitude of marginal costs of production was explored. It should be noted that while assessing efficiency of ports' operations, this indicator is often used as optimality criterion. This is explained by the fact that a port has traditionally focused on minimizing production costs associated with cargo handling. However, under modern conditions of tough competition in the port business, a port should primarily focus on the interests of clients, including consideration of alternative options of development of handling equipment fleet. In this regard, it is justifiable to choose not a strategy that makes it possible to minimize costs (or maximize profit), but rather the strategy, slightly inferior from the position of anticipated economic indicators, but significantly enhancing the quality of port services. In this regard, to substantiate the strategy of development of port handling equipment, there is a need to develop appropriate quantitative methods for assessing effectiveness, taking into consideration features of functioning of port-specific systems under conditions of tough competition.

Previous studies on the port operation optimization have already attempted to take into account and formalize the interests of shipowners and cargo owners with the help of a single integral indicator. Thus, in [8], devoted to studying issues of interaction between ports, shipowners, and cargo owners, as well as the issues of competition in the maritime transport market, there was an attempt to formalize the maritime transport chain as an equilibrium model. However, due to increasing difficulty, related to the creation of a unified model of functioning of ports and maritime transport market, a number of aspects of operation of ports or market of marine freight transportation had to be omitted or taken into account in a simplified form. "Packing" all indicators of a complex system as a single integral indicator is a convenient formalization for a mathematical optimization model. However, reducing the studies into such a multifaceted and complex system as a system of relations "ports – cargo owners – ship owners" to an analysis of only one indicator of "total costs" makes it impossible to explore deep processes and relationships between subsystems.

The indicated drawback is supposed to be eliminated by using an alternative approach based on an analysis and multicriteria optimization of each of the subsystems. Under this approach, it is also advisable to identify the Pareto frontiers of unimproved values of indicators of subsystems' performance. Then, on the obtained Pareto frontiers, it is necessary to search for compromise solutions, which are the most suitable for a system as a whole. The latter approach is associated with some difficulties, but it also enables us to assess more accurately and analyze the boundaries of effective operation of each of the subsystems. This makes it possible to identify bottlenecks, detect contradictions in interaction and development of subsystems, and to identify promising directions of development.

3. The aim and objectives of the study

The aim of present research is to construct and analyze the model of substantiation of the optimal structure of the port handling machinery fleet, which provides a balance between economic indicators of port's performance and an average vessels' berthing time.

To accomplish the aim, the following tasks have been set:

– to investigate dependence of average annual production costs and profit of production transshipment complex (PTC) on the structure of handling equipment fleet;

– to explore the problems of multicriteria optimization of the structure of handling machinery fleet;

– to analyze a set of Pareto-optimal solutions of multicriteria optimization problem.

4. Materials and methods to study the problem of substantiation of the structure of handling machinery fleet

Let us consider PTC, which consists of four berths, the limit concentration of handling machinery on each of which includes four machines. Handling machinery fleet consists of n_{st} stationary and n_{mob} mobile machines. We will assume that stationary machines are evenly distributed between the berths and, unlike mobile machines, they cannot move freely between berths. To study performance indicators of this PTC, in [9] the apparatus of Markov chains was used. In [9], the equations were constructed for finding values $p_{b_1b_2b_3b_4}$ (b_1, b_2, b_3, $b_4 \in \{0, 1\}$) of probabilities that at any arbitrary moment the PTC will be in state $A_{b_1b_2b_3b_4}$, in which b_1 of vessels of PTC will be found at the first berth, b_2 of vessels will be at the second berth, b_3 – at the third berth, b_4 – at the fourth berth, and no ships will lie out. We will also find values p_i (i=1, 2,...) of probabilities that at any arbitrary moment of time, the system will be in state A_i, in which all the berths will be occupied, and i vessels will lie out. Based on these probabilities, assessments of various performance indicators of PTC were obtained, in particular, a dependence of vessels' berthing time on the structure of handling equipment fleet was explored. Table 1 and Fig. 1 show results of calculations of vessels' berthing time depending on the structure of machinery fleet operating at PTC [9]. Results were obtained for the case when performances of stationary and mobile machines are identical and comprise 100 t/h, while intensity of cargo traffic, passing through the terminal is 4.9 million t/year. As Fig. 1 and Table 1 show, the shortest vessels' berthing time is achieved at maximum saturation of the fleet with mobile equipment.

Now we will study dependence of average annual costs and profit of PTC on the structure of the handling equipment fleet.

Average annual profits of PTC ($\overline{P}$) can be derived from formula

$$\overline{P} = \overline{I} - \overline{C}, \tag{1}$$

where $\overline{I}$ is the average annual income, obtained from load handling; $\overline{C}$ is the average annual costs of PTC.

Table 1

Average vessels' berthing time (h)

Number of mobile machines	Total number to handling machines at PTC								
	8	9	10	11	12	13	14	15	16
0	93.9	76.5	64.9	57.5	53.2	46.7	42.3	39.7	38.4
1	87.8	73.6	61.5	53.2	48.0	45.0	41.2	39.2	38.4
2	82.7	67.7	58.9	51.4	46.0	42.6	40.7	39.1	38.4
3	79.2	64.7	55.7	50.5	45.1	42.2	40.1	39.0	38.4
4	77.0	62.8	53.6	47.8	44.5	41.9	40.0	39.0	38.4
5	73.4	61.4	52.3	47.2	43.8	41.8	39.9	39.0	38.4
6	70.6	58.4	51.4	46.8	43.5	41.2	39.8	39.0	38.4
7	68.3	57.4	50.5	46.6	43.4	41.0	39.8	39.0	38.4
8	66.8	56.6	50.2	45.8	43.2	40.9	39.8	39.0	38.4
9	–	56.2	49.8	45.6	42.6	40.8	39.8	39.0	38.4
10	–	–	49.6	45.3	42.4	40.8	39.8	39.0	38.4
11	–	–	–	45.2	42.2	40.8	39.8	39.0	38.4
12	–	–	–	–	42.1	40.8	39.8	39.0	38.4
13	–	–	–	–	–	40.8	39.8	39.0	38.4
14	–	–	–	–	–	–	39.8	39.0	38.4
15	–	–	–	–	–	–	–	39.0	38.4
16	–	–	–	–	–	–	–	–	38.4

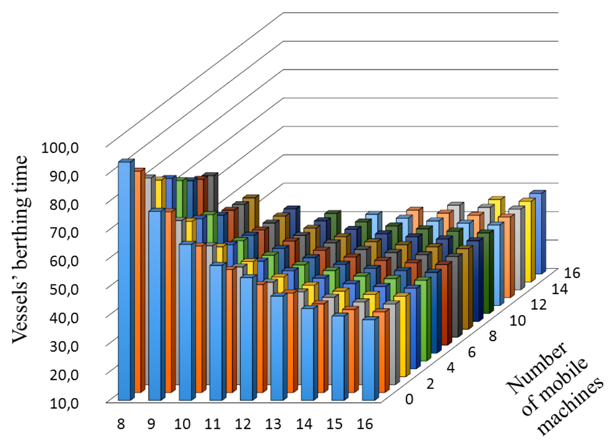

Fig. 1. Average vessels' berthing time (h)

Income ($\overline{I}$) of a port operator is calculated from formula:

$$\overline{I} = \overline{Q} \cdot r^{inc}, \quad (2)$$

where $\overline{Q}$ is the average amount of cargo, transshipped by PTC within a year (t); r^{inc} is the income rate for handling of one ton of cargo (USD/t).

$$\overline{C} = \overline{C}_{equip} + \overline{C}_{gen} + \overline{C}_{berth}, \quad (3)$$

where $\overline{C}_{equip}$ are the total annual costs of equipment; $\overline{C}_{gen}$ are the average annual costs of general nature, including administrative costs; $\overline{C}_{berth}$ is the charge of a port operator for services of providing access to berths within a year in accordance with the Decree of the Cabinet of Ministers of Ukraine dated 14.12.2015, No. 1331-2015-r.

$$\overline{C}_{equip} = \overline{C}_{oper} + \overline{C}_{cap}, \quad (4)$$

where $\overline{C}_{oper}$ are the average annual total operating costs of equipment, including costs of fuels and lubricants, electricity, equipment maintenance, depending on the volume of output; $\overline{C}_{cap}$ is the average annual total capital costs – costs for purchase of production equipment, its overhauls and upgrades, as well as costs for the purchase of tools, which provide equipment operation.

Total operation costs ($\overline{C}_{oper}$) for equipment are determined as

$$\overline{C}_{oper} = \overline{C}^{const}_{oper} + \overline{C}^{var}_{oper}, \quad (5)$$

where $\overline{C}^{const}_{oper}$ are the constant operating costs that do not depend on the level of equipment usage (including wages of maintenance personnel and routine technical check-ups irrespective of equipment operation); $\overline{C}^{var}_{oper}$ is the variable operating costs, depending on the level of equipment usage (including costs of energy and consumables).

Constant operating costs ($\overline{C}^{const}_{oper}$) can be calculated from formula

$$\overline{C}^{const}_{oper} = n_{mob} \cdot \overline{r}^{const}_{mob} + n_{st} \cdot \overline{r}^{const}_{st}, \quad (6)$$

where n_{mob} is the number of mobile machines at PTC; n_{st} is the number of stationary machines at PTC; $\overline{r}^{const}_{mob}$ is the annual amount of constant operating costs for one mobile machine (USD); $\overline{r}^{const}_{st}$ is the average annual amount of constant operating costs for one stationery machine (USD).

Variable operating costs ($\overline{C}^{var}_{oper}$) can be calculated from formula

$$\overline{C}^{var}_{oper} = \overline{B}^{op}_{mob} \cdot \overline{r}^{op}_{mob} + \overline{B}^{op}_{st} \cdot \overline{r}^{op}_{st}, \quad (7)$$

where $\overline{r}^{op}_{mob}$ is the average amount of variable operation costs within a day of operation of one mobile machine (USD/day); $\overline{r}^{op}_{st}$ is the average amount of variable operation costs within a day of operation of one stationary machine (USD/day); $\overline{B}^{op}_{mob}$ is the total average annual output of the whole fleet of mobile machines (day); $\overline{B}^{op}_{st}$ is the total average annual output of the whole fleet of stationary machines (day).

Total average annual output for mobile ($\overline{B}^{op}_{mob}$) and stationary ($\overline{B}^{op}_{st}$) machines can be calculated from formulae

$$\overline{B}^{op}_{mob} = T \cdot \sum_{b_1 b_2 b_3 b_4} p_{b_1 b_2 b_3 b_4} \cdot n^{mob}_{b_1 b_2 b_3 b_4} + T \cdot n_{mob} \cdot \sum_i p_i, \quad (8)$$

$$\overline{B}^{op}_{st} = T \cdot \sum_{b_1 b_2 b_3 b_4} p_{b_1 b_2 b_3 b_4} \cdot n^{st}_{b_1 b_2 b_3 b_4} + T \cdot n_{st} \cdot \sum_i p_i, \quad (9)$$

where T is the annual time budget (days); $n^{mob}_{b_1 b_2 b_3 b_4}$ is the number of mobile machines, engaged in cargo operations when PTC is in state $A_{b_1 b_2 b_3 b_4}$; $n^{st}_{b_1 b_2 b_3 b_4}$ is the number of stationary machines, engaged in cargo operations when PTC is in state $A_{b_1 b_2 b_3 b_4}$.

Values $n^{mob}_{b_1 b_2 b_3 b_4}$ and $n^{st}_{b_1 b_2 b_3 b_4}$ are determined by discipline movable equipment, mounted between berths at PTC, and depend on the structure of machinery fleet, existing location of stationary machines on berths, a berth line configuration of PTC and limits of machinery concentration on berths. Determination of values $n^{mob}_{b_1 b_2 b_3 b_4}$ and $n^{st}_{b_1 b_2 b_3 b_4}$ in each particular case presents no difficulties. Table 2 shows, as an example, some values $n^{mob}_{b_1 b_2 b_3 b_4}$ and $n^{st}_{b_1 b_2 b_3 b_4}$ for PTC with broken berthage, on which it is impossible for stationary machinery to motion, equipped with n_{st}=9 stationary machines and n_{mob}=7 mobile machines. The limit concentration of handling equipment at each berth is 4 machines, stationary machines are distributed between berths as follows: 3, 2, 2, 2.

Table 2

Some values of $n^{mob}_{b_1 b_2 b_3 b_4}$ and $n^{st}_{b_1 b_2 b_3 b_4}$ at n_{st}=9 and n_{mob}=7

$A_{b_1 b_2 b_3 b_4}$	$n^{st}_{b_1 b_2 b_3 b_4}$	$n^{mob}_{b_1 b_2 b_3 b_4}$
A_{0000}	0	0
A_{1000}	3	1
A_{0100}	2	2
A_{1100}	5	3
...	...	...
A_{1111}	9	7
A_i (i=1, 2,...)	9	7

Annual average capital costs ($\overline{C}_{cap}$) of equipment are calculated from formula

$$\overline{C}_{cap} = n_{mob} \cdot \frac{C_{mob}}{T^{serv}_{mob}} + n_{st} \cdot \frac{C_{st}}{T^{serv}_{st}}, \tag{10}$$

where C_{mob} are the costs of purchasing of one mobile machine, costs of introducing it in operation and utilization, of all major overhauls and modernization until decommission, as well as costs for small-scale mechanization, which provide operation; C_{st} are the costs of purchasing of one stationary machine, costs of introducing it in operation and utilization, all major overhauls and modernization, as well as costs of small-scale mechanization; T^{serv}_{mob} is the service life of one mobile machine; T^{serv}_{st} is the service life of one stationary machine.

When evaluating C_{mob} and C_{st}, in the case when the equipment has long service life, it might make sense to use discounting.

Charge of a port operator for services on providing access to berths ($\overline{C}_{berth}$) within a year is equal to

$$\overline{C}_{berth} = \overline{Q} \cdot r^{berth}, \tag{11}$$

where r^{berth} is the tariff rate for services of providing access of a port operator to a berth per unit of cargo of the i-th vessel's batch (USD/t).

For subsequent analysis, we will assume that $\overline{r}^{const}_{mob}$ = =3.6 thousand USD, $\overline{r}^{const}_{st} = 2.88$ thousand USD, $\overline{r}^{op}_{mob} = 1$ thousand USD, $\overline{r}^{op}_{st} = 0.8$ thousand USD, C_{mob}=1.3 USD mln, C_{st}=USD 1.5, $T^{serv}_{mob} = 15$ years, $T^{serv}_{st} = 20$ years, r^{berth}=USD 0.3, r^{inc}=USD 4. Results of calculation of values $\overline{C}_{equip}$ and average annual profit (based on dependences (1)–(11)) for PTC under consideration at different structures of machinery fleet are shown below.

Next, based on existing dependences of costs, income and average vessels' berthing time at PTC, it is possible to explore the problems of multicriteria optimization of the structure of machinery fleet.

a) Let us explore the problem of substantiation of the structure of handling machinery fleet, in which berthing time of vessels and of PTC costs should be minimal. We will designate a set of all permissible structures of machinery fleet as Θ. Then the problem of multicriteria optimization can be written down in the form of

$$\underset{\theta \in \Theta}{\text{minimize}}\, \vec{F}(\theta), \tag{12}$$

where

$$\vec{F}(\theta) = \left(\overline{C}_{equip}(\theta), \overline{Y}(\theta)\right)$$

is the vector objective function, the first coordinate of which is function of total average costs of equipment depending on the structure of machinery fleet, and the second coordinate is function, which expresses average berthing time of vessels, depending on the machinery fleet structure.

Because high-performance equipment is not always the most economical and vice versa, the most economical equipment often is not the most effective, generally speaking, it is not possible to expect existence of one solution to this problem (12). That is why in the course of studying of a set problem, it is advisable to use approaches, applied in the theory of multicriteria assessment. One of the key concepts of the theory of multicriteria assessment is the concept of a set of points of unimprovable Pareto solutions [10]. Unimprovable solution is the one, in which improvement of one of the goals leads to inevitable deterioration of at least one of the others. Only unimprovable solutions are of practical interest.

There are a number of analytical methods for finding a set of unimprovable solutions [10]. The simplest methods are based on reducing the multicriteria problems to the scalar ones by constructing weighted sums of so-called convolutions However, this approach makes it impossible to conduct analysis of relationships between criteria. That is why in this research we do not set the goal to find criteria convolutions, but rather to construct and analyze the whole Pareto frontier.

Using the resulting dependences of total costs and vessels' berthing time, we will find a set of unimprovable structures of machinery fleet and correspondent Pareto set.

b) Let us explore the problem of substantiation of the structure of handling machinery fleet, in which vessels' berthing time should be minimal, and profit of PTC – maximal.

Let us consider the multicriteria optimization problem

$$\underset{\theta \in \Theta}{\text{minimize}}\, \vec{F}_1(\theta), \tag{13}$$

where

$$\vec{F}_1(\theta) = \left(-\overline{P}(\theta), \overline{Y}(\theta)\right)$$

is the vector objective function, the first coordinate of which expresses total profit of PTC depending on the structure of machinery fleet, and the second coordinate is the average vessels' berthing time.

Using resulting dependences of profit of PTC and vessels' berthing time, we will find a set of unimprovable structures of machinery fleet and a corresponding Pareto set.

5. Results of study of the problem of substantiation of structure of handling machinery fleet

The results of calculations of values $\overline{C}_{equip}$ for PTC under consideration at different structures of machinery fleet are shown in Table 3 and in Fig. 2. Table 4 and Fig. 3 show the values of average annual profit of PTC at different structures of handling fleet.

Table 3

Total annual costs of equipment at different structures of machinery fleet (USD, mln)

Number of mobile machines	Total number of handling machines at PTC								
	8	9	10	11	12	13	14	15	16
0	4.5	4.9	5.2	5.6	6.0	6.3	6.7	7.1	7.4
1	4.6	5.0	5.4	5.7	6.1	6.5	6.8	7.2	7.5
2	4.8	5.2	5.5	5.9	6.2	6.6	6.9	7.3	7.6
3	4.9	5.3	5.6	6.0	6.3	6.7	7.0	7.4	7.7
4	5.1	5.4	5.8	6.1	6.5	6.8	7.1	7.5	7.9
5	5.2	5.5	5.9	6.2	6.6	6.9	7.3	7.6	7.9
6	5.3	5.7	6.0	6.3	6.7	7.0	7.4	7.7	8.0
7	5.4	5.8	6.1	6.5	6.8	7.1	7.5	7.8	8.2
8	5.6	5.9	6.2	6.6	6.9	7.3	7.6	7.9	8.3
9	–	6.0	6.3	6.7	7.0	7.4	7.7	8.0	8.4
10	–	–	6.5	6.8	7.1	7.5	7.8	8.2	8.5
11	–	–	–	6.9	7.2	7.6	7.9	8.3	8.6
12	–	–	–	–	7.4	7.7	8.0	8.4	8.7
13	–	–	–	–	–	7.8	8.1	8.5	8.8
14	–	–	–	–	–	–	8.3	8.6	8.9
15	–	–	–	–	–	–	–	8.7	9.0
16	–	–	–	–	–	–	–	–	9.2

Table 4

Average annual profit of PTC at different structures of machinery fleet (USD, mln)

Number of mobile machines	Total number of handling machines at PTC								
	8	9	10	11	12	13	14	15	16
0	10.2	10.1	9.8	9.5	9.1	8.8	8.4	8.1	7.7
1	10.1	9.9	9.7	9.3	9.0	8.6	8.3	8.0	7.6
2	10.0	9.8	9.5	9.2	8.9	8.5	8.2	7.8	7.5
3	9.9	9.7	9.4	9.1	8.8	8.4	8.1	7.7	7.4
4	9.8	9.6	9.3	9.0	8.6	8.3	8.0	7.6	7.3
5	9.6	9.4	9.2	8.9	8.5	8.2	7.9	7.5	7.2
6	9.5	9.3	9.0	8.7	8.4	8.1	7.7	7.4	7.1
7	9.4	9.2	8.9	8.6	8.3	8.0	7.6	7.3	7.0
8	9.3	9.1	8.8	8.5	8.2	7.9	7.5	7.2	6.8
9	–	9.0	8.7	8.4	8.1	7.7	7.4	7.1	6.7
10	–	–	8.6	8.3	8.0	7.6	7.3	7.0	6.6
11	–	–	–	8.2	7.9	7.5	7.2	6.8	6.5
12	–	–	–	–	7.7	7.4	7.1	6.8	6.4
13	–	–	–	–	–	7.3	7.0	6.7	6.3
14	–	–	–	–	–	–	6.9	6.5	6.2
15	–	–	–	–	–	–	–	6.4	6.1
16	–	–	–	–	–	–	–	–	6.0

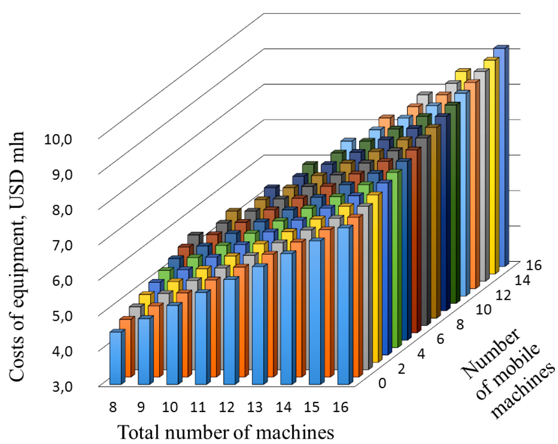

Fig. 2. Average annual costs of equipment for different structures of machinery fleet

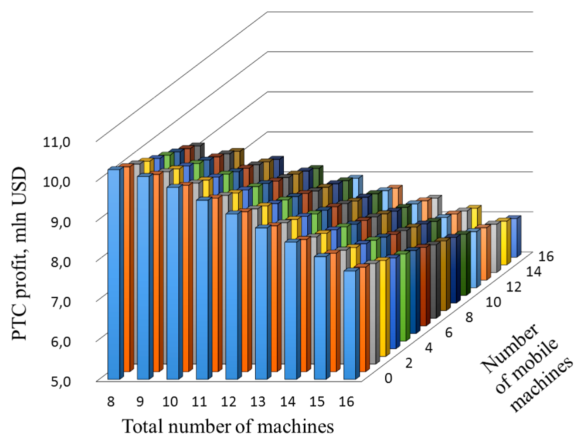

Fig. 3. Average annual PTC profit for different structures of machinery fleet

Using resulting dependences of total costs and vessels' berthing time, we will find a set of unimprovable structures of machinery fleet and the correspondent Pareto set for multicriteria optimization problem (12). Table 5 shows unimprovable solutions to the problem (12), lying on the Pareto frontier, and their corresponding structures of handling machinery fleet. In Fig. 4, each point corresponds to a particular structure of handling equipment fleet at PTC, and the points, lying on the Pareto frontier, are marked with arcs.

We will note that not all structures of handling machines that were optimal in terms of one-criterion optimization, got to the Pareto frontier of multicriteria assessment problem. Thus, for example, among all equipment fleets, consisting of 12 machines, the shortest vessels' berthing time was provided by structure $S_{12,0}$, however, it was not included in the Pareto frontier.

All points in Fig. 4, which did not enter Pareto frontier, have no practical interest for a decision maker (DM), because there is at least one point on the Pareto frontier, both criteria of which are not worse and at least one is better. That is why all points that did not enter the Pareto frontier, are deliberately inefficient, and therefore can be excluded from consideration. Thus, after constructing the Pareto frontier, it is possible to cut off most deliberately ineffective solutions. Among the points, lying on the Pareto frontier, some of them are characterized by short average berthing time, the others – by low costs of PTC, and some have balanced values of these two parameters. In this case, they are all unimprovable and it is impossible to give preference to one of the solutions on the Pareto frontier without involving any additional reasoning. That is why for final selection of the machinery fleet structure from all the alternatives, presented on the Pareto frontier, it is necessary to involve experts. Based on consideration of additional factors, own experience and intuition, as well as assessments of associate experts, only a decision-maker can make a final choice from all the alternatives on the Pareto frontier. Although knowledge of the Pareto frontier does not give explicit solution of the problem of substantiation of the structure of machinery fleet, it allows cutting off a large part of deliberately inefficient solutions that did not enter the Pareto frontier. This enables experts to make a choice from a small number of unimprovable solutions. It is intuitively clear, that, as a rule, the most high-quality service (from the position of the established criterion) may not be the most affordable. In this regard, only a DM, guided by additional knowledge and observations, which may lie beyond the mathematical model, can choose the most balanced ratio of price and quality. In this case we are talking about relationship between average level of costs and average level of berthing time. And the use of methods for multicriteria evaluation in this situation allows us to dramatically simplify the problem of such choice for DM by reducing a set of all possible solutions to a small subset.

For the multicriteria optimization problem (13), the Pareto curve is shown in Fig. 5.

In this case, the same structures of the machinery fleet correspond to the points on the Pareto frontier for profit (Fig. 5) and to the points on the Pareto frontier for costs of equipment (Fig. 4). It should be noted that it is not always the case. If we consider in calculations the cargo traffic, depending on average berthing time $\overline{Q}=\overline{Q}(\overline{Y})$, instead of permanent cargo traffic, the points on the Pareto frontiers for profit and costs may correspond to different structures of handling equipment. The study of dependence of cargo traffic intensity on average berthing time is a separate problem. Solution of this problem involves the study of port competition, markets of global and regional production, transport infrastructure and other features that affect the port operation outside the scope of this article.

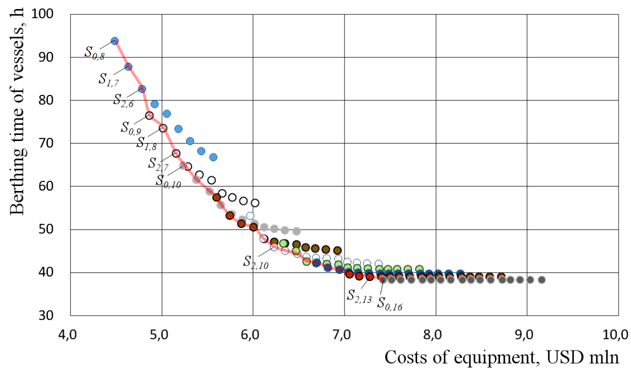

Fig. 4. Points of unimprovable values of average berthing time of vessels and average annual costs of equipment of PTC for different structures of equipment fleet

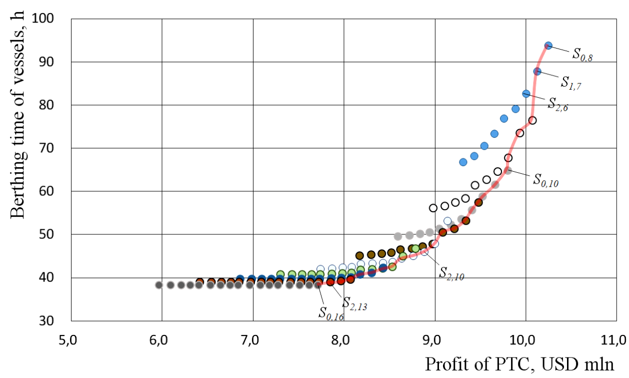

Fig. 5. Points of unimprovable values of average berthing time of vessels and average annual profit of PTC for various structures of equipment fleet

Each structure of machinery fleet, considered here, allows handling the assigned flow. At the same time, indicators of vessels' service quality and costs of cargo handling may vary in quite wide ranges depending on the choice of one or another structure. The Pareto frontiers, shown in Fig. 4 and Fig. 5, provide a possibility to draw some conclusions. Thus, if PTC authorities seek to minimize costs and in this case berthing time is virtually not taken into account, it is advisable to select structure of machinery fleet $S_{0,8}$.

Table 5

Points of unimprovable values for problem of multicriteria optimization of totality of average costs of equipment and vessels' berthing time depending on structure of machinery fleet

Designation of structure of machinery fleet, Sn_{mob}, n_{st}	Total number of machines, $n_{mob}+n_{st}$	Number		Vessels' berthing time, $\overline{Y}$, h	Costs of equipment of PTC, $\overline{C}_{equip}$, USD, mln	Profit of PTC, $\overline{P}$, USD, mln
		of mobile machines, n_{mob}	of stationary machines, n_{st}			
$S_{0,8}$	8	0	8	93.9	4.5	10.2
$S_{1,7}$	8	1	7	87.8	4.6	10.1
$S_{2,6}$	8	2	6	82.7	4.8	10.0
...	...	...	...	...	...	...
$S_{2,10}$	12	2	10	46.0	6.2	8.9
...	...	...	...	...	...	...
$S_{2,13}$	15	2	13	39.1	7.3	7.8
$S_{0,16}$	16	0	16	38.4	7.4	7.7

In this case, average annual costs of PTC for equipment will amount to USD 4.5 million, and average berthing time will be 93.9 h. If berthing time is important from the position of DM, having selected $S_{0,16}$ structure instead of $S_{0,8}$ structure, it is possible to reduce average vessels' berthing time, but at the same time costs of equipment of PTC will nearly double. Based on results obtained, structures of machinery fleet $S_{3,9}$, $S_{2,10}$, $S_{1,11}$, $S_{3,8}$, $S_{2,9}$, $S_{1,10}$ or $S_{0,11}$. may seem the most balanced. Because total costs of equipment for these machinery fleet is only USD 1.5 million more than those for the most economical machinery fleet, but in this case, average berthing time of vessels is approximately half as much.

6. Discussion of results of the study of problem of substantiation of the structure of handling machinery fleet

When substantiating the structure of handling equipment fleet, in order to enhance competitive ability of efficiency of functioning of modern port systems, it is not sufficient to take into account any particular factor. It is necessary to consider their totality. Existence of Pareto frontiers, received in the course of the study of the proposed multicriteria optimization problem, facilitates for PTC authorities the decision on substantiation of the structure of handling machinery fleet. As a result, the selected option takes into account the needs of PTC, cargo owners and ship owners, as well as provides maximum balance between their interests.

Research has shown that among the points, lying on the Pareto frontier, some are characterized by short average berthing time, the other – by low costs of PTC, and some have balanced values of these two parameters. In this regard, it is expedient to conditionally divide the Pareto frontier, consisting of unimprovable values of average vessels' berthing time and average annual profit of PTC, into three parts (Fig. 6).

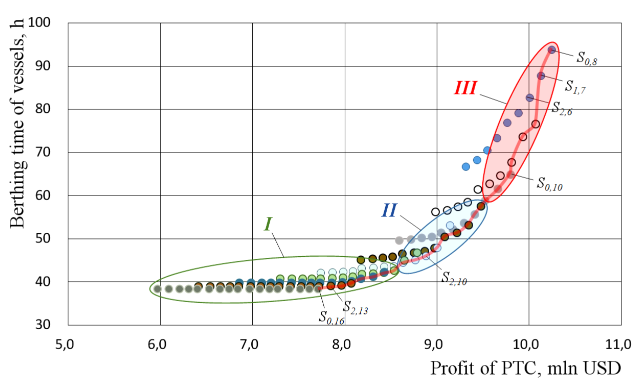

Fig. 6. Three types of unimprovable structures of port handling equipment: productive, cost-effective, balanced

In the first region, the best values of berthing time of vessels is achieved. However, in this case, average profit of PTC remains minimal. Thus, in order to decrease berthing time only by 1 %, being in this area, it will be necessary to "sacrifice" about 4 % of profit. In the third region, by contrast, maximum profit of PTC is achieved due to a reduced number of reloading machines. In doing so, an increase in profit by only 10 % in the third area is accompanied by loss of quality of servicing ships by more than 30 %. The most balanced ratio between profit and vessels' berthing time in found in the second region.

It should be noted, however, that all the points that lie on the Pareto frontier, are unimprovable and it is impossible to give preference to one solution on the Pareto frontier without involving any additional reasoning. Only based on consideration of other factors, own experience and intuition, as well as assessment of associate experts, a decision-maker can make a final selection of all alternatives available on the Pareto frontier.

In this study, only one criterion of vessels' service quality was considered, but perhaps consideration of other criteria is possible. For example, one can explore a share of ships, the handling time of which exceeds a certain magnitude, etc. The studies, presented in this work, were limited to consideration of two-criterial optimization problems. When choosing an optimal structure of handling machinery fleet, it is possible to consider even more criteria. The greatest difficulties, when researching problems with lots of criteria, are caused not by computational aspects, but rather by problems, related to visualization of multi-dimensional Pareto frontier.

In the present research, only two alternative types of equipment were considered, but this approach allows exploration of problems with a larger number of equipment types. In doing so, the number of possible ways to equip the PTC fleet with handling equipment will increase significantly, and, accordingly, the effect of implementation of the approach, proposed in this work, will increase.

7. Conclusions

The problem of substantiation of the structure of handling machinery fleet was formulated and solved in this research. Its implementation is based on the methods of multicriteria optimization and makes it possible to achieve, on the one hand, balanced average indicators of costs and profit of a sea terminal, and, on the other hand, berthing time of vessels. To do this, in this work:

1. Dependence of average annual costs and profit of the production transshipment complex on the structure of the fleet of handling equipment was examined by means of the methods of theory of mass service. Unlike non-stochastical techniques, the proposed approach allows evaluation of indicators of a seaport performance under condition of uneven, randomly changing cargo traffic.

2. Problems of multicriteria optimization of the structure of handling machinery fleet were explored with the use of approaches based on finding a set of unimprovable solutions by constructing and analyzing all Pareto frontier. The proposed approach, in contrast to other analytical methods, based on reducing multicriteria problems to scalar problems by constructing weighted sums, allows us to analyze relationship between the criteria.

3. A set of Pareto-optimal solutions of multicriteria optimization problems was analyzed. Obtained results enable us to make a reasonable choice of optimum structure of fleet of the port handling equipment, taking into account the needs of PTC, shipowners and cargo owners to achieve a maximum balance between their interests.

References

1. Talley, W. K. Port service chains and port performance evaluation [Text] / W. K. Talley, M. Ng, E. Marsillac // Transportation Research Part E: Logistics and Transportation Review. – 2014. – Vol. 69. – P. 236–247. doi: 10.1016/j.tre.2014.05.008
2. Bergantino, A. S. The role of external factors versus managerial ability in determining seaports' relative efficiency: An input-by-input analysis through a multi-step approach on a panel of Southern European ports [Text] / A. S. Bergantino, E. Musso // Maritime Economics & Logistics. – 2011. – Vol. 13, Issue 2. – P. 121–141. doi: 10.1057/mel.2011.1
3. Kirillova, E. V. Justification of stability ranges of commercially reasonable, allowable loss-making and crisis operation of the vessel [Text] / E. V. Kirillova // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 6, Issue 3 (78). – P. 4–10. doi: 10.15587/1729-4061.2015.55007
4. Kirillova, Y. V. Justification of financial safety analysis approach in cargo-and-passenger ferry operations management [Text] / Y. V. Kirillova, Y. S. Meleshenko // Transport and Telecommunication Journal. – 2014. – Vol. 15, Issue 2. – P. 111–119. doi: 10.2478/ttj-2014-0010
5. Budiono, A. The development of a queuing model for optimization of seaport facilities at Tanjung Perak seaport, Indonesia [Text] / A. Budiono // IOSR Journal of Mechanical and Civil Engineering. – 2016. – Vol. 13, Issue 6. – P. 93–100.
6. Wan, Y. Strategic investments in accessibility under port competition and inter-regional coordination [Text] / Y. Wan, L. J. Basso, A. Zhang // Transportation Research Part B: Methodological. – 2016. – Vol. 93. – P. 102–125. doi: 10.1016/j.trb.2016.07.011
7. Díaz-Hernández, J. J. The effects of ignoring inefficiency in the analysis of production: The case of cargo handling in Spanish ports [Text] / J. J. Díaz-Hernández, E. Martínez-Budría, S. Jara-Díaz // Transportation Research Part A: Policy and Practice. – 2008. – Vol. 42, Issue 2. – P. 321–329. doi: 10.1016/j.tra.2007.10.002
8. Talley, W. K. Maritime transport chain choice by carriers, ports and shippers [Text] / W. K. Talley, M. Ng // International Journal of Production Economics. – 2013. – Vol. 142, Issue 2. – P. 311–316. doi: 10.1016/j.ijpe.2012.11.013
9. Malaksiano, M. O. Otsinka tryvalosti obslugovuvannia suden na terminali z riznotypnym ustatkuvanniam [Text] / M. O. Malaksiano // Metody ta zasoby upravlinnia rozvytkom transportnykh system. – 2008. – Issue 14. – P. 108–124.
10. Ehrgott, M. Multicriteria optimization [Text] / M. Ehrgott. – 2nd ed. – Berlin: Springer, 2005. – 323 p. doi: 10.1007/3-540-27659-9