One of the main tasks in stability calculations is to provide the ship with the necessary (optimal) trim whose final value is influenced by the arrangement of cargo on the ship. Today, however, there are rules and requirements but there is no unified approach to developing a cargo plan for a vessel that simultaneously transports various types of general cargo.

In order to improve the efficiency of the above calculations, a procedure has been proposed to optimize developing a cargo plan for a vessel carrying heterogeneous general cargoes at the same time, the main idea of which is to distribute consignments on the ship in two stages, taking into consideration the compensating trimming moment. The scheme to develop a cargo plan has been improved by introducing the developed procedure. The results of verification confirmed its effectiveness in practice.

Possible deviations of the values for the trim required (optimal) for the voyage from the actual one calculated after the allocation of stocks and consignments of goods have been investigated using an example of the series of developed cargo plans. It should be noted that the value for the trim, required (optimal) and actual, for each individual cargo plan does not differ by more than 8 %.

The results reported in this paper give grounds to assert the expediency of their application when developing cargo plans for tramp shipping vessels. The introduction of the procedure could make it possible to effectively load a vessel with the full utilization of both its carrying capacity and cargo capacity. The use of the proposed scheme for developing a cargo plan to transport heterogeneous cargoes would reduce the total time for calculating the stability and strength of the vessel in general

Keywords: cargo plan, trim, general cargo, trimming moment, stability of the vessel

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OPTIMIZATION OF THE STAGES OF A SHIP'S CARGO PLAN DEVELOPMENT FOR SHIPPINING OF GENERAL CARGOES

Oleksandr Loshkarov
Senior Lecturer
Department of Economics and Maritime Law*
Olga Kornelyuk
Corresponding author
Senior Lecturer
Department of Ship Handling at Sea*
E-mail: olganikkornelyuk@gmail.com
*Kherson State Maritime Academy
Ushakova ave., 20, Kherson, Ukraine, 73000

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1. Introduction

Since the second half of the twentieth century, the transportation of goods by sea has been developing very intensively, which is associated with the global growth of commodity production and foreign trade volumes. The maritime industry is undergoing a series of transformations related to the situation in the world in general, but sea freight does not lose its superiority compared to other techniques of cargo transportation [1].

Since the advent of maritime transport, the development of cargo transportation technology has taken place in three directions. This is a change in the design of the hull of the vessel for the convenience of transporting specific goods; optimization of cargo placement on the vessel; transformation of cargo into a state convenient for sea transportation. Among the huge number of types of ships operated in the modern merchant fleet, three main ones are in the lead, in which the specialization of the vessel and the adaptability of goods for transportation have reached perfection [2]. These are container ships, bulk carriers (for bulk cargo), tankers (for liquid cargo).

At the same time, container transportation is experiencing difficulties. We are talking about queues created by ships in the port in anticipation of unloading [3]. Therefore, the direction of transportation of small consignments of heterogeneous general cargoes, which, for a series of reasons, cannot be placed in containers, remains relevant. And this is an extremely profitable solution for ports that do not have, for example, container terminals, for small ports in size and depth, etc. Containers are quite capital-intensive and are not economically profitable with small volumes of transportation. Thus, this study is aimed at optimizing the technique of developing a cargo plan when loading a vessel with heterogeneous general cargoes with different transport characteristics.

2. Literature review and problem statement

One of the primary issues solved even before the start of loading operations in the port is the preparation of a cargo plan (hereinafter, Cargoplan). The computer technology market offers a lot of modern solutions for automating such a task on a turnkey basis. For example, programs such as Videck Stowage Planning [4], SimpleStow GC [5] make it possible to plan the placement and move consignments of cargo along the vessel on the screen. The software contains restrictions that control the norms of correct placement of goods.

General cargoes during transportation by sea must be placed taking into consideration their transport and operational characteristics, as well as the table of compatibility of goods. Then only it is possible to ensure the safety of the properties, for example, of the cargo, susceptible to odors, loads, etc. However, when using the software described in [4, 5], accounting for the features (danger, dustiness, heat generation, etc.) of the goods combined during loading is not solved automatically and is performed exclusively under the control of the operator (senior assistant).

With a small aft trim, the efficiency of the propulsion systems increases and most ships increase the speed of the course. However, a further increase in the trim leads to a decrease in speed. The nose trim, due to an increase in the resistance of water to movement, typically leads to a loss of forward speed [6]. This is one of the most important factors of ship safety at sea [7].

The influence of trim values on the seaworthiness of the hull of the vessel has been confirmed by numerous publications. Among them, paper [8] reports a developed panel method for optimizing the trim of the hull, where the wave resistance is used as an objective function. As part of research [9], the optimal trim value was proposed for the navigation of the container ship hull. In [10], the study showed that the optimal trim mainly depends on the draught of the vessel and the state of the sea. The results reported in [11] indicate the effectiveness of the application of CFD-modeling of the hull flow of the vessel, taking into consideration the free surface of the liquid at the stage of finding the optimal trim of the vessel for navigation. It is also noted in [11] that the nose trim can reduce resistance at low Froud numbers. However, as the Froud number increases, the minimum resistance is usually achieved by aft trim. It is shown that CFD-modeling of the hull flow of the vessel in order to establish the optimal value of the trim for operation is one of the ways to save fuel in the voyage. However, the publications do not address the issue of providing the vessel with the required trim every time at the planning stage of loading the vessel in port.

When moving cargo along the hull, the vessel's trim changes depending on the draft of the bow and stern [7]. Therefore, if one registers the values of the deadweight and net carrying capacity of the vessel, then for a series of developed cargo plans, the trim would take different values. Everybody knows that a vessel would be trimmed relative to the point *F* (Center of flotation), as shown in Fig. 1, where draft1, ..., draft5 is the average draught of the vessel.

If the trim is not satisfactory, adjustments are made to a Cargoplan. Changing the value of the trim, guided by the Instructions to the captain, can be made by ballasting the vessel or moving the cargo [12]. However, there may be many options for placing consignments of general cargo with different characteristics (Cargo 1, Cargo 2, ... CargoN) (Fig. 3). In addition, the value of the trim is affected by the stocks placed on the vessel per voyage, light ship.

Programs such as LoadSafe Loading calculator software [13], ShipLoad [14], ShipStab [15], etc., it would seem, can be a solution to the problem of calculating the trim in the conditions of operation of the vessel. However, the specified software types are suitable for the carriage of one type of cargo. An option for overcoming the current situation for tramp shipping vessels is to search for new approaches to developing cargo plans and ensuring the required trim in the port when loading a vessel. All this suggests that it is advisable to conduct a study on the optimization of technology for developing Cargoplan for ships carrying several types of general cargo at the same time.

3. The aim and objectives of the study

The aim of this work is to optimize the calculations related to developing a cargo plan for a vessel carrying heterogeneous general cargoes at the same time, in particular, the task of allocating consignments of goods on the condition that the vessel is provided with an optimal value of the trim.

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

– to develop a procedure for optimizing a cargo plan development;

– to offer an improved scheme for developing a cargo plan;

– to verify the results of using the improved scheme in practice.

4. The study materials and methods

At the initial stage of the study, we analyzed results from works on this subject area published earlier. By synthesis, conclusions have been drawn about the lack of a unified approach to developing a plan for arranging the general cargo on a ship. CFD modeling makes it possible to determine with sufficient accuracy a value for the optimal trim during navigation for a particular vessel. However, the decisive measure in the operation of the vessel from day to day is to ensure this trim at each loading of the vessel in port.

Verification of the research results was carried out using an example of a double-deck vessel with an engine room and a superstructure in the stern. Its bow tip is bulbous, and the stern is cruising. The vessel is intended for transportation of general cargo, industrial equipment, and grain. T-shaped cranes execute any kind of loading and unloading operations. The schematic drawing of the vessel is shown in Fig. 1.

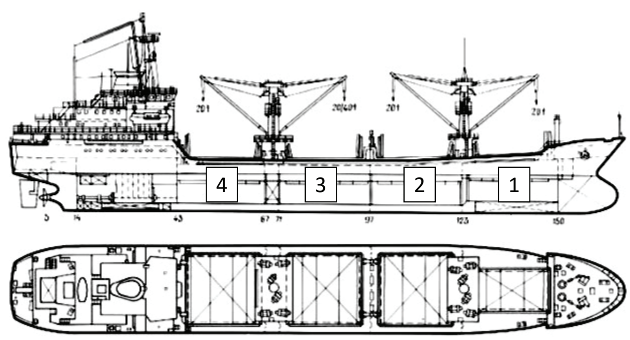

Fig. 1. Double-deck vessel [16]

Table 1 gives the vessel's specifications, the distributed load in the compartments, the list of mandatory and alternative cargoes for developing a cargo plan for the vessel. A compartment in this context denotes a room consisting of a hold and a corresponding twin deck located above it.

The distributed loads of the cargo spaces given in Table 1 are calculated before the stage of placing consignments on the vessel as part of devising a Cargoplan according to the following formulas:

$$P_{b_i} = \frac{W_{b_i}}{\omega_b}, \tag{1}$$

$$P_{a_i} = \frac{W_{a_i}}{\omega_a}, \tag{2}$$

where W_{b_i} is the bale capacity of the i-th bow compartment, m^3; W_{a_i} is the bale capacity of the i-th aft compartment, m^3; ω_b is the weighted average specific cargo capacity of bow compartments, m^3; ω_a is the weighted average specific cargo capacity of aft compartments, m^3.

The Cargoplan development diagram shown in Fig. 2 is just great for ships carrying one type of cargo at the same time, whether it is bulk cargo or general cargo. In this case, the classical method of optimal trim and consistent allocation of cargo in the compartments make it possible to devise an optimal Cargoplan much faster than for a vessel carrying heterogeneous general cargo at the same time. The task is also complicated by the transport and operational characteristics of each individual type of cargo and the need for their correct placement during transportation by sea.

Thus, using an example of a series of devised cargo plans for the transport of heterogeneous general cargoes according to the scheme (Fig. 2), it was determined that a given scheme requires improvement. At the initial stage, the weight load for each cargo compartment is calculated using an optimal trim method. However, often, due to the different volumetric and weight characteristics of individual loads, the actual load may be quite different from the set and the trim must be corrected. In practice, this is possible by moving consignments with different specific loading volumes (Stowage Factor) [17] from one compartment to another with further recalculation of the trim, which is a time-consuming process. Obviously, there can be a huge number of options for redistributing the general cargo "by eye". Thus, it is not possible to avoid cycles in the process (Fig. 2) until the seaworthiness of the vessel is satisfactory.

Table 1

Characteristics of the vessel and cargo for transportation

Load line	Summer
Draft in sea water	6.92 m
Displacement	9,124 t
Net lifting capacity	5,444 t
Stocks	213 t
Stock Moments	
– relative to midship	1,184 tm and –5,576 tm
– relative to the main plane	962 tm
Optimal trim	–0.45 m
Distributed loads	compartment 1 – 1,005 t
	compartment 2 – 1,455 t
	compartment 3 – 1,482 t
	compartment 4 – 1,502 t
Compulsory cargo range (weight/weight with separation)	rapeseeds 550/552 t
	equipment 800/806 t
Alternative cargo	spare parts 400/402 t
	rolled products and cardboard containers

Operational trimming is carried out by moving the masses while the resulting trimming moment is the cause of the vessel's trim (Fig. 3). It has been suggested that the "unused" trimming moment when loading in some compartments can be taken into consideration when distributing the remaining masses of cargo in other compartments. Thus, the concept of a compensating trimming moment emerged, and it was proposed to divide devising a plan for arranging the batches of the general cargo into two stages. The built mathematical model has made it possible to devise a procedure for simplifying the preparation of a cargo plan and eliminating the element's cycle loop on the scheme (Fig. 2).

By using the method of comparison of the vessel's cargo plans, devised according to the general scheme and in line with to the improved procedure, we drew conclusions about the convergence of calculations in both cases. However, the time spent on devising a cargo plan for a vessel when using the developed procedure has significantly decreased, and the difference between the optimal and actual trims is more insignificant than when using the scheme in a general form.

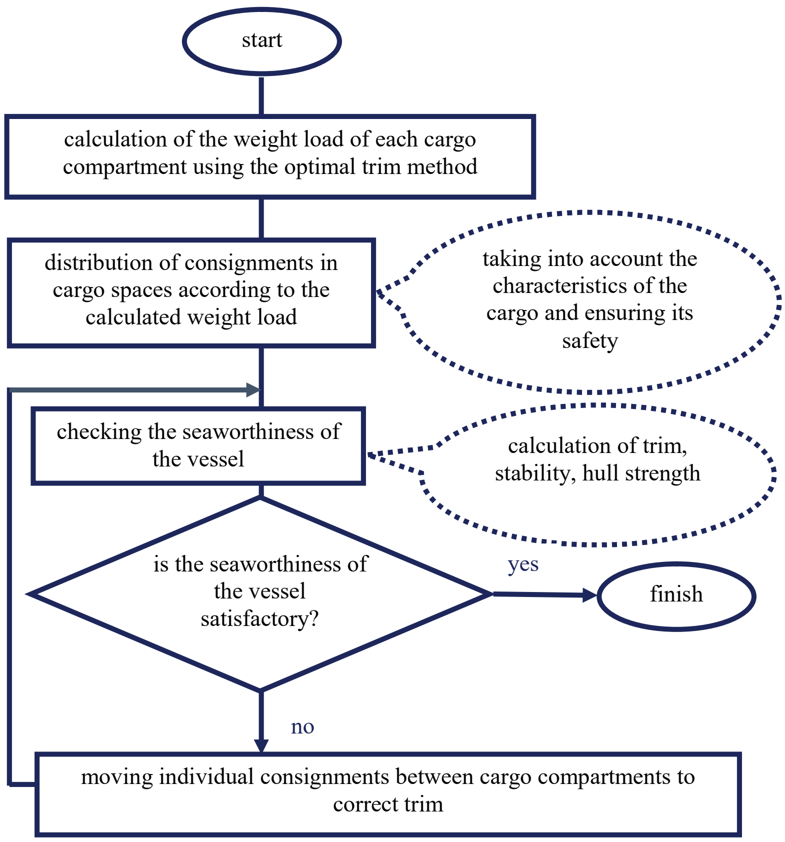

Fig. 2. Cargoplan development scheme in a general form

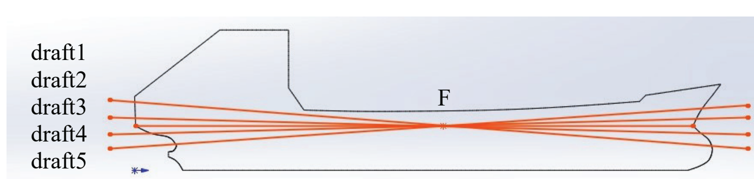

Fig. 3. Change in a trim when moving a load along the hull

5. Results of studying the issue of improving the efficiency of devising a cargo plan for a ship carrying general cargoes

5. 1. Procedure to optimize devising a cargo plan

The essence of our procedure is that the allocation of consignments is made in two stages and is accompanied by the implementation of certain calculations. A detailed algorithm of the devised procedure is shown in Fig. 4.

At the first stage, part of the cargo is distributed in compartments symmetrical with respect to the midsection. Among the ship compartments, for Phase 1 (Fig. 5), two are selected, located symmetrically to the midsection, and not having curvilinear surfaces. For example, for a vessel with five holds, compartments 2 and 4. Accordingly, in the second stage, the goods are distributed in compartments 1, 3, and 5, taking into consideration their transport characteristics, in compliance with the local and general strength of the vessel. At the same time, it is desirable to distribute mainly small consignments of cargo with "complex" transport characteristics to these premises. To some extent, this is facilitated by the fact that there is no need to try to put the amount of cargo in these compartments that is close to the distributed load. If the vessel has an even number of cargo compartments (for example, 4), then initially the cargo is distributed in compartments 1 and 3, and then in compartments 2 and 4 (Fig. 1).

The amount of cargo in them may differ from the distributed mass. If it is impossible to place loads proportionally to the distributed mass, it is recommended to load with a deviation not exceeding 10 % of the norm. Then one should calculate the deviations of weight and moments in the already loaded compartments. The principle of calculation is illustrated by an example in Table 2.

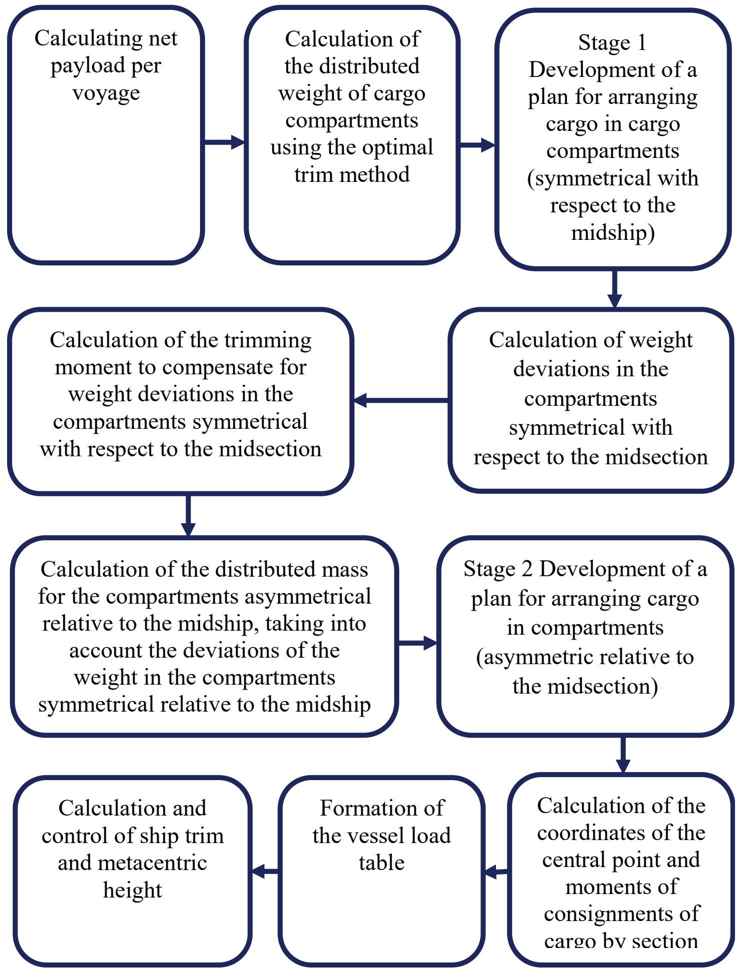

Fig. 4. Algorithm of the procedure for simplifying the task of devising a Cargoplan for vessels that transport heterogeneous general cargoes

Table 2

Distribution of consignments on the example of compartments 1 and 3 of a double-deck vessel

Cargo space name	Cargo capacity, m^3/weight, t (max)	Cargo 1, t (actual)	Cargo 2, t (actual)	Cargo 3, t (actual)	Cargo total weight, t	Weight deviation, t
Twindeck 1	721, 563	Rapeseeds, 383	absent	absent	383	–180
Hold 1	566, 442	Equipment, 165	absent	absent	165	–277
Total for compartment 1	1,005				548	–457
Twindeck 3	870, 680	Rapeseeds, 169	Spare parts, 98	Rolled steel, 603	870	+190
Hold 3	1,027, 802	Equipment, 230	Rolled steel, 603	absent	833	+31
Total for compartment 3	1,482				1,703	+221

The algorithm for calculating the compensating trimming moment is given in Table 3.

In Table 2, m is the total deviation of weight in compartments located symmetrically relative to the midsection; $M_{trim\ comp}$ – compensating trimming moment.

In the second stage, the cargo is distributed in compartments that are asymmetrical relative to the midsection, taking into consideration the compensating trimming moment. To this end, the following equation is built:

$$m_x * x_1 + (m - m_x) * x_2 = M_{trim\ comp}, \qquad (3)$$

where m is the total deviation of weight in the compartments, t (Table 1);

$M_{trim\ comp}$ is the compensating trimming moment, tm (Table 1);

m_x is the deviation from the distributed weight in one of the compartments located asymmetrically relative to the midsection, t;

$(m - m_x)$ is the deviation from the distributed weight in another compartment located asymmetrically relative to the midsection, t;

x_1, x_2 are the corresponding arms, m.

The result of solving the equation makes it possible to determine exactly how much weight should be added to the distributed mass in each compartment placed asymmetrically relative to the midsection. This approach would provide the vessel with the specified trim, reducing the total calculation time.

Table 3

Calculation of compensating trimming moment

Compartment name	Weight deviation, t	Arm X, m	Moment relative to midsection, tm
Compartment 1	m_1	x_1	M_1
Compartment 2	m_2	x_2	M_2
...	...	...	...
Compartment 3	m_n	x_n	M_n
Total moment	$m=\Sigma m_i$, $i=1,...,n$		$M_{trim\ comp}=\Sigma M_i$, $i=1, ..., n$

5. 2. The improved scheme of cargo plan development

Fig. 5 shows an improved scheme for preparing a cargo plan using the devised procedure (Fig. 4). We give the results of the option of loading a double-deck vessel with the full utilization of both its carrying capacity and cargo capacity. This is the most difficult case to compile a Cargoplan.

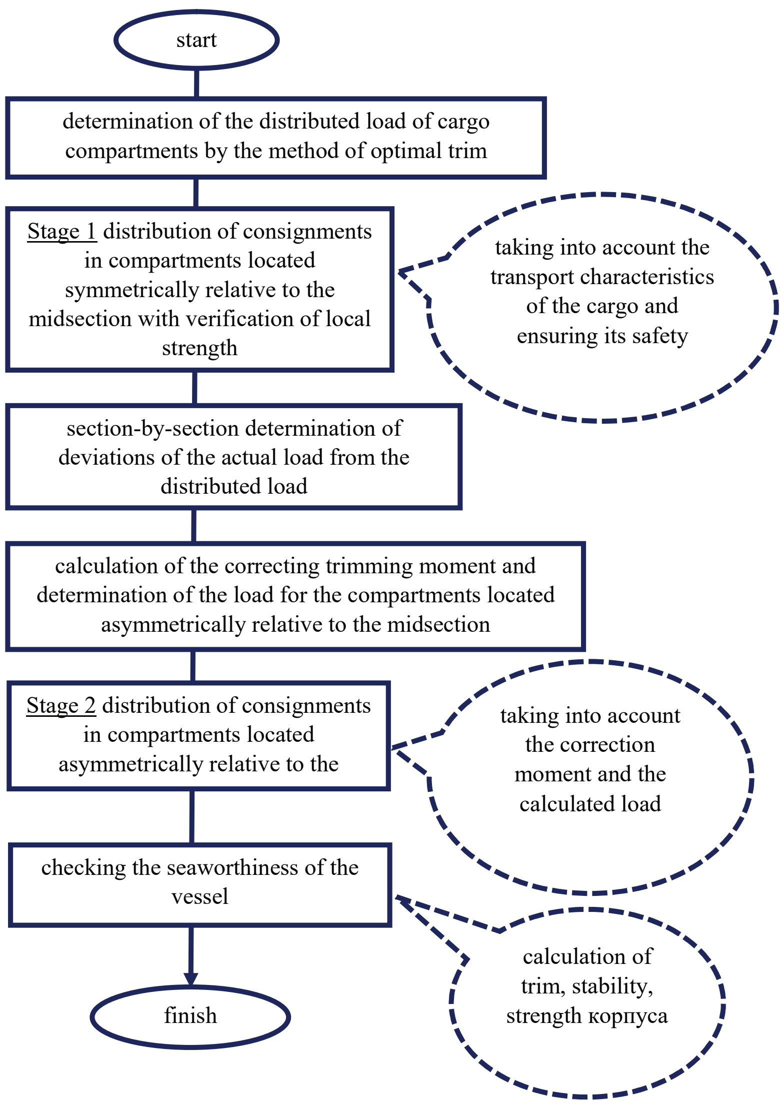

Fig. 5. Improved Cargoplan development scheme

By allocating consignments in the cargo compartments in two stages and taking into consideration the compensating trimming moment (in stage 2), it was possible to eliminate the cycle loop when devising a Cargoplan scheme.

5. 3. Verification of the results of using the improved scheme in practice

Arrangement of general cargo requires a preliminary calculation of the number of places in each cargo hold. This is due to the linear dimensions of a particular cargo in the package or without it, as well as the size of the cargo compartment itself. In this case, the weight of separation is added to the weight of the cargo.

Below, Table 4 gives as an example the results of planning the placement of cargo in hold 3, located symmetrically relative to the midsection. It contains such types of cargo as rolled steel and equipment.

Brief entry for Hold 3 (weight, cargo height, clearance/separation): equipment – 230 t/2.2 m/0.25 m; rolled steel – 603 t/1.1 m/0.05 m. Corresponding calculations were performed for other cargo compartments. Table 1 gives an example of the result of cargo allocation in compartments 1 and 3. Table 5 gives the result of cargo allocation in compartments 2 and 4, taking into consideration the compensating trimming moment.

Table 4

Planning of cargo placement in Hold 3

Cargo	Rolled steel and equipment
Rolled steel layer	Along 2 rows per 31 cassettes; transverse in 2 rows per 2 cassettes
Total per layer: number of cassettes	2*31+2*2=66
total weight of cassettes	66*4.5=297 t
height of the cassette with separation	0.55 m
Number of rolled layers	2
height of cassettes with separation	1.1 m
weight of cassettes without separation	594 t
weight of cassettes with separation	594*1.015=603 t
Separation height from cargo separation boards	0.05 m
Number of equipment layers	2
Volume	2.2*17.8*16.2=634 m^3
total equipment weight	230 t
Clearance	0.25 m

4 tons of the vessel's carrying capacity were not used in the allocation, which is less than the weight of 1 place in the cargo hold (4.5 tons).

Next, the seaworthiness of the vessel is checked. According to (4), the actual trim of the vessel is determined as:

$$TRIM = \frac{\Delta \times (x_G - x_C)}{MTC}, \quad (4)$$

the value of which in devising a Cargoplan for a double-deck vessel was –44 cm. The vessel has a trim on the stern. Given the value of the optimal trim preset before devising the cargo plan, it is less by 1 cm (Table 1).

The calculation results of local strength are satisfactory, as evidenced by Table 6.

Having distributed the cargo in the holds, the Cargoplan form is to be filled.

As part of our study into the feasibility of applying in practice the procedure described in this paper for ships carrying simultaneously different types of general cargo, cargo plans have been devised under different loading conditions using an example of the same vessel (Fig. 1). The main purpose was to establish the difference between the optimal trim of the vessel, specified at the beginning of the calculations, and the actual trim calculated after the placement of consignments on the ship. The results are plotted in Fig. 6.

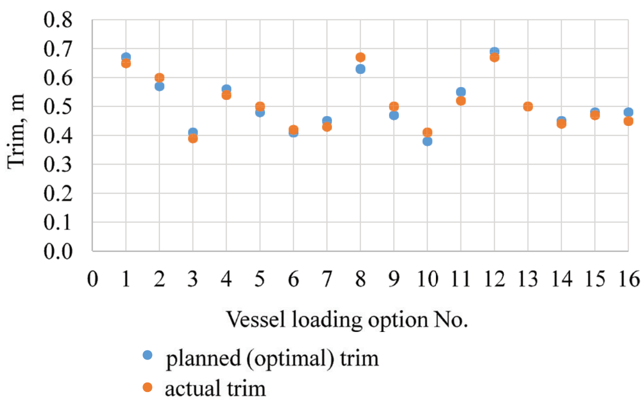

Fig. 6. Plot comparing trim values for different vessel loading options

Analyzing the study results, we can say that the improved scheme for devising a cargo plan definitely has its advantages.

6. Discussion of results of investigating the task of improving the efficiency of devising a cargo plan for a vessel carrying general cargo

In the field of maritime transportation, there are rules and requirements but there is no single approach to devising a cargo plan for a vessel while simultaneously transporting different types of general cargo. That is why the task of optimizing the stability calculations of such vessels is relevant.

In this regard, within the framework of the research, an algorithm of the procedure for simplifying the task of drawing up a cargo plan has been developed (Fig. 4). Its essence is the allocation of consignments in two stages and taking into consideration the compensating trimming moment when working on the arrangement of goods in cargo compartments.

This paper gives the algorithm for calculating the compensating trimming moment (Table 3), as well as equation (1), solving which would make it possible to correctly place the cargo in the compartments at the second stage of the improved Cargoplan development scheme (Fig. 5). Due to this, the calculation time is reduced, the ship is provided with an optimal (specified) trim, and it becomes possible to reduce the number of iterations at the stage of ensuring seaworthiness to a loaded ship, in contrast to the diagram in Fig. 2.

The devised procedure, as well as the improved scheme for the development of the cargo plan of the vessel, are optimal for use on tramp shipping vessels when the vessels are not tied to specific geographical points and are convenient to use for the transportation of small consignments of various general cargoes.

The presented advanced scheme of Cargoplan development is applicable for dry cargo universal vessels with at least three holds.

One of the limitations of our study results and, at the same time, the next stage of research is the need to automate calculations according to the algorithms and formulas reported in the present work. At the same time, it is obvious that difficulties can be encountered, such as taking into consideration the transport and operational character-

Table 5

Allocation of consignments in compartments 2 and 4

Cargo space name	Cargo capacity, m^3/weight, t (max)	Cargo 1, t (actual)	Cargo 2, t (actual)	Cargo 3, t (actual)	Cargo total weight, t	Weight deviation, t
Twindeck 2	902, 705	Spare parts, 169	Rolled steel, 544	absent	713	–8
Hold 2	960, 750	Equipment, 110	Rolled steel, 1206	absent	1,316	+566
Total for compartment 2	1,455	Plan – 2,002			Actual 2,029 (+27)	+558
Twindeck 4	855, 698	Tare, 12	Spare parts, 135	Rolled steel, 603	750	+52
Hold 4	984, 804	Equipment, 301	Tare, 109	absent	410	–394
Total for compartment 4	1,502	Plan – 1,191			Actual 1,160 (–31)	–342

Table 6

Calculation of local strength

Cargo space name	Actual load, t/m^2	Permissible load, t/m^2
Twindeck 1	1.8	4
Hold 1	1.2	5
Twindeck 2	2.5	4
Hold 2	4.6	5
Twindeck 3	3.3	4
Hold 3	3.0	5
Twindeck 4	2.8	4
Hold 4	1.4	5

istics of the vessel, such as the compatibility of the types of general cargo located in one compartment, when distributing consignments in the cargo compartments. However, in the creative work of a chief mate there are solutions that do not exclude the human factor and cannot be programmed.

7. Conclusions

1. A special feature of the proposed procedure is to break up the process of distributing consignments into compartments in two stages, which is absent in the conventional scheme of Cargoplan development. Based on the calculated value for the compensating trimming moment, an equation is built. As a result of solving it, it is possible to determine exactly how much weight should be added to the distributed mass of each compartment loaded in the second stage of consignment allocation. This approach would provide the vessel with the predefined trim, reducing the total calculation time.

The results of studying the effectiveness of the devised procedure in practice indicate an excellent convergence of the process of calculating the vessel's trim. When calculating a series of cargo plans for a vessel, the maximum deviation of the actual value of the trim from the planned (optimal) is not more than 8 %. As regards the effect of such a deviation on the value of the trim, the following should be noted. If the value of the calculated actual trim differs from the planned optimal by 8 %, then, in centimeters, this difference would not exceed 3 cm, which is not significant for dry cargo vessels of tramp shipping.

2. Improved through the devised procedure, the scheme for developing a cargo plan for a vessel has been adapted for the development of cargo plans of tramp shipping vessels carrying heterogeneous general cargo at the same time. The number of possible types of cargo planned for transportation is not limited to one or two or more.

Unlike the existing scheme, the improved scheme eliminates the cycle loops of certain stages when devising a Cargoplan. This reduces the number of calculated iterations and provides the vessel with an optimal trim during the development of Cargoplan, the calculation of which is an integral part of calculating the stability of the vessel in general. A satisfactory value of the trim, in turn, would provide the vessel with excellent handling, maneuverability, and running, as well as increase the speed of the vessel without increasing fuel consumption.

3. The study carried out within the framework of verification of the results indicates the advantage of the improved scheme over the generally accepted one, since it is devoid of a multi-iterative process at the stage of ensuring the vessel's seaworthiness. The introduction of an improved scheme in practical calculations could allow for a more efficient loading of a vessel with the number of holds three or more with the full utilization of both its carrying capacity and cargo capacity. This is a profitable solution for ports where there are no container terminals or when it is required to transport small volumes of cargo. For such ports, as well as for shallow ports, there is a prospect of developing such tramp shipping along with container transportation.

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