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Selection of optimal parameters of soft parallelepiped-shaped containers

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ABSTRACT

The paper addresses the issues related to the containerization of cargo transportation processes. Containers of various types and designs are now widely used in logistics and technological operations for transporting substantial volumes of goods. They form an independent category of transport equipment, characterized by well-defined technical parameters and specialized fittings, enabling efficient mechanized loading and unloading operations. The use of containers significantly increases the efficiency of both the transportation process and the associated cargo-handling, as well as warehousing activities. A promising direction for improving bulk material transportation technologies is the active implementation of soft containers in product supply logistics schemes. The use of such equipment is technically convenient and economically justified, particularly for temporary storage and transportation of large consignments of bulk cargo. The specific features of using soft containers with a parallelepiped shape as a modern and promising type of transport equipment in technologies for delivering bulk and loose cargoes were analyzed. These soft container models are simple to manufacture and are sufficiently widespread in the market. The advantages of using this type of equipment were highlighted. The need to account for possible transverse deformation of the walls of soft containers when determining the feasibility of their placement within the cargo compartments of vehicles was also emphasized. The magnitude of these deformations depends on several factors, the key ones being the properties of the bulk cargo, the geometric parameters of the container, and the mechanical characteristics of its shell material. The most significant influence on wall deformation is exerted by the container dimensions, the bulk density of the material, and the coefficient of friction between the cargo and the container walls. The properties of the shell material are also of considerable importance, including its strength, stiffness, thickness, fiber structure, and overall fabric condition. Taking these factors into account, the paper proposes approaches to solving optimization problems aimed at selecting rational parameters for soft parallelepiped-shaped containers to achieve maximum utilization of the cargo space of a vehicle, considering the deformation of the container shells.

Keywords: containers, cargo transportation, bulk cargo, deformation factor.

INTRODUCTION

The application of modern technical and technological solutions in the field of freight transportation significantly accelerates and enhances the efficiency of product delivery to end consumers [1, 2]. Unexpected conditions often reveal lack of infrastructure and insufficient conditions [3, 4]. At the same time, it is necessary to ensure reliable storage of cargo and improve the level of safety of transport operations [5, 6]. It does not matter what type of transport it is [7]. One of such solutions, validated by global practice, is containerization [8, 9]. There are still efforts to develop sustainable, effective and efficient transport means for high speed and safe transportation of goods [10, 11]. These efforts of engineers in the field of transport and mechanical engineering result in new technical solutions of containers [12, 13]. The containers that allow being transported by several transport means were characterized [14, 15]. There are mainly road vehicles, rail vehicles as well as ships [16, 17]. A significant advantage of rail transport is lower drag, when wagons are set to a long train [18, 19]. The sustain transport and low pollution of the environment in the case of rail vehicles is strengthen mainly in case of using electric traction vehicles [20, 21] However, it is necessary to consider the load of containers due to running on track irregularities [22, 23]. They lead to excitation of a mechanical system of containers [24]. Therefore, the structure of containers should be properly designed to resist the external load factors of the track during operation [25, 26]. Internal goods loaded into them also affect their properties [27].

Bulk and loose cargoes account for a substantial share of global freight turnover. Their transportation is subject to increasingly stringent requirements regarding safety, preservation of product quality, selection of rational transportation technologies, and monitoring of the technical condition of rolling stock. Traditional methods of transporting such cargoes are based on the use of universal or specialized vehicles across different modes of transport. However, in practice, there is often a shortage of specialized rolling stock, which necessitates the search for and implementation of new, more efficient technological solutions for bulk material transportation. This enables an increase in the overall efficiency of the transport process [28, 29] and better satisfaction of the needs of all participants in the logistics chain [4].

In this context, the scientifically substantiated selection of parameters of transport packaging and auxiliary equipment becomes particularly relevant [30]. These decisions directly affect the efficiency of cargo placement in warehouses and in the cargo compartments of vehicles, as well as the level of mechanization of cargo-handling and warehousing operations.

At present, containers of various designs are widely used in technological processes for transporting large volumes of cargo [31]. They constitute a distinct category of transport equipment with established technical characteristics and specialized fittings for the mechanized handling of transshipment operations. The use of containers improves the efficiency of both the transportation process and the associated cargo-handling and warehousing activities.

One of the promising directions for improving bulk material delivery technologies is the introduction of soft containers (hereinafter referred to as SC) into product supply logistics schemes. The use of such equipment is technically convenient and economically justified, particularly under conditions of temporary storage and transportation of large consignments of bulk cargo. Soft containers are characterized by reliability, simplicity of design, and ease of manufacture. They are most commonly produced from polypropylene fabric and, when filled, typically assume a parallelepiped or cylindrical shape. Owing to their versatility, soft containers can be effectively handled by various types of lifting equipment, which makes them an important element of modern transport equipment [30].

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The introduction of soft containers has significantly improved the efficiency of solving technological problems associated with cargo transportation. Artificial intelligence is also one of the factors, which affects the trends in freight transport logistics [32]. In particular, it has become possible to substantially reduce product losses at all stages of its circulation and decrease the costs of cargo-handling operations.

An analysis of scientific and technical sources devoted to technologies for the use of soft containers in cargo transportation has revealed a number of important advantages of such solutions compared to traditional methods [33].

The main advantages include:

- reduction in the need for specialized rolling stock, which is often in short supply,
- significant decrease in cargo losses during transportation,
- improvement of conditions for maintaining product cleanliness and quality,

- enhancement of environmental protection and protection of transport vehicles from the potential negative impact of cargo,
- elimination of the need to clean vehicles after transportation,
- creation of conditions for temporary outdoor storage of certain types of cargo, which makes it possible to significantly reduce the costs of constructing warehouse premises.

Modern technologies make it possible to manufacture soft containers of virtually any geometric shape. The most common are the models that, when filled, assume a parallelepiped or cylindrical form.

To improve the efficiency of cargo transportation in soft containers, it is essential to ensure the maximum utilization of both the cargo capacity and payload capacity of vehicles. Therefore, when organizing transportation processes, particular attention should be paid to the selection of soft container parameters, taking into account the physicomechanical properties of the specific cargo [34]. The selected container dimensions and the characteristics of the loaded materials directly affect the level of utilization of vehicle capacity and payload capacity. At present, this aspect remains insufficiently addressed. The efficiency of placing SCs in vehicle cargo compartments is also influenced by various factors, in particular the deformation of the soft container shell under the action of bulk material, which can significantly alter its initial geometry.

Soft containers with a parallelepiped shape are widely used for transporting bulk cargoes. Theoretically, such a container has a square cross-section with side length b and height h. However, under real operating conditions, the container shell deforms under the weight of the bulk material, deviating from its initial geometry.

To assess such deformations and loss of the correct geometric shape, continuum mechanics approaches are used, which describe the behavior of soft shells with limited tensile capacity. These models take into account the effect of the pressure of the bulk material on the container walls. A significant number of scientific works are devoted to the issues of mechanical properties of deformed shells. In particular, in [35] the results of studies of the compressive strength of flexible shells were presented, in [36] the FEM analysis of the deformation of bags filled with cargo was performed. The project [37] was aimed at studying internal stresses in flexible containers based on experimental and numerical methods. The dynamic aspects of the operation of elastic shells were considered in [38, 39]. In [40] the results of modeling the behavior of fibrous packaging materials under triaxial compression were presented. The study of similar issues was devoted, for example, to works [40–42]. These studies highlight the issues of stiffness, deformation and compaction, which is of great importance for understanding the mechanical behavior of the walls of flexible containers and the pressure distribution of bulk cargo inside them.

One of the key aspects of the studies is the safety of transportation. In study [43], the risks of deformation and displacement of SC during sea transportation are examined in detail. The authors emphasized that dynamic loads (ship rolling) lead to loss of stacking stability and potential damage to the container shell. Strict compliance with the ISO 21898 standard regarding maximum compression and stacking height is strongly recommended.

BSEE Safety Alert [44] focuses on the incidents of sling failure during SC lifting. The document describes several near-miss cases caused by sling brittleness at low temperatures and uneven load distribution. It highlights the need for regular testing and strict adherence to the safe working load (SWL) with a safety factor of no less than 5:1.

Logistical operations were addressed in the FIBCA study [45]. It provided comprehensive recommendations on filling, storage, transportation, and unloading of SC, with a strong emphasis on ergonomics, contamination prevention, and optimization of warehouse processes. These recommendations form the foundation for many industries.

In article [46], Palmetto Industries analyzed the evolution of SC within supply chains. The authors emphasized the advantages of the container flexibility for multimodal transportation and predict increased use of antistatic and UN-certified models for hazardous cargoes.

Study [47] examined the use of UN-certified SC for dangerous goods. It emphasized the importance of compliance with UN standards for the packaging of hazardous materials (UN FIBC) and conducting tests for resistance to static electricity.

Thus, a significant number of studies focus on the mechanical stability of the container shell, the safety of transportation and cargo handling operations (especially with hazardous goods and during lifting), and the optimization of logistical processes involving flexible containers. At the same time, the optimal selection of geometric parameters for parallelepiped-shaped SC - taking into account deformation and maximum utilization of load capacity - remains insufficiently studied. This article aimed to bridge this gap.

RESEARCH OBJECTIVE

The aim of the work was to clarify the approaches to solving optimization problems regarding the selection of rational parameters of soft containers, which have the shape of a parallelepiped, in accordance with the characteristics of the cargo, the dimensions of the cargo compartment of the vehicle, and the possible deformation of the container shell.

MAIN RESEARCH MATERIAL

Let us consider the problem of selecting rational parameters of soft parallelepiped-shaped containers, namely those with a square cross-section, depending on the dimensions of the cargo compartment of the vehicle and the bulk density of the transported material.

Under optimal loading of a vehicle, the following conditions must be satisfied simultaneously:

- the vehicle load G_B should be utilized maximally without exceeding its payload capacity,
- the number of soft containers K_{ijk} of a given standard size *ij* should be minimized: $K_{ijK} \rightarrow \min$,
- the mass of a single soft container G^1_{ijk} [kg] of the selected standard size *ij* must not exceed the allowable limit: $G^1_{ijk} \leq G^1_{max}$,
- the strength of the SC with its required load capacity is technologically ensured.

As the *ij*-th standard size of a soft container with a square cross-section, a combination of its two main parameters– width b_i and height h_j – was considered.

The number K_{ijk} of containers of the *ij*-th standard size filled with bulk cargo *k* of bulk density γ_k, that can be accommodated in a vehicle can be determined as follows:

$$K_{ijK} = N_i \cdot M_i \cdot Z_{ij} \quad (1)$$

where: N_i – the number of SC of the *ij* -th size that can be loaded across the width of the cargo space, M_i – the number of SC of the *ij*-th size that can be loaded across the length of the cargo space, Z_{ij} – the number of loading tiers of containers of the *ij* -th size in the cargo space.

The volume of one SC will be:

$$V_{ij} = b_i^2 \cdot h_j \quad (2)$$

With known internal dimensions of the vehicle's cargo space: width *B*, length *L* and height *H*, the following expressions can be written:

$$N_i = \left[\frac{B}{b_i}\right], M_i = \left[\frac{L}{b_i}\right], Z_j = \left[\frac{H}{h_j}\right] \quad (3)$$

Square brackets […] denote the values of the corresponding expressions, rounded down to the nearest integer.

The total load G_{ijk} of a vehicle with bulk cargo *k* with bulk mass γ_k [kg] loaded into K_{ijk} soft containers will be:

$$G_{ijk} = K_{ij} \cdot V_{ij} \cdot \gamma_k = \\ = N_i \cdot M_i \cdot Z_{ij} \cdot b_i^2 \cdot h_j \cdot \gamma_k \quad (4)$$

In the general case, to choose rational SC parameters, it is necessary to solve the optimization problem:

$$G_{ijk} = f(N_i, M_i, Z_{ij}, b_i^2, h_j, \gamma_k) \rightarrow G_B^{max} \quad (5)$$

This problem can be solved using known mathematical methods, taking into account the following restrictions:

$$b_i^{\min} \leq b_i \leq b_i^{\max}, \quad h_j^{\min} \leq h_j \leq h_j^{\max}, \\ G_B \leq G_B^{max}, \quad G^1_{ijk} \leq G^1_{max}. \quad (6)$$

In the cases where the goal is to minimize the number of containers that must be used to fully load the cargo space of a vehicle, it is necessary to solve an optimization problem of the form:

$$K_{ijK} = N_i \cdot M_i \cdot Z_{ij} \rightarrow min \quad (7)$$

taking into account the same constraints of the form (6).

As an example, Figure 1 presents the results of optimizing the objective function of type (7) subject to the above constraints (6) for selecting the parameters *b* and *h* of a soft container in the case of transporting bulk cargo *k* with bulk density γ_k, loaded into K_{ijk} soft containers. The discrete optimization problem [48, 49] was solved using MS Excel by means of the evolutionary Solver method [50]. For the calculations, the following parameters were adopted: the vehicle - a standard semi-trailer (euro truck) with a payload capacity of G^{max} = 20 t and internal body dimensions B = 2.45 m, L = 13.6 m, H = 2.5 m. The soft containers were loaded in a single layer.

The calculations yielded the minimum number of soft containers required for full utilization of the vehicle with the specified cargo compartment dimensions for any value of bulk density, namely K_{ijk}. The optimal width of the container side is b =1.2 m. The optimal height h of the soft container significantly depends on the bulk density and decreases nonlinearly with an increase in the bulk density γ_k.

Considering the relatively low cost of a single soft container, to improve transportation efficiency through a more complete utilization of the vehicle payload capacity, it is often necessary to optimize the SC parameters specifically based on an objective function of type (5).

Figure 2 depicts selected results of such optimization subject to the constraints (6), with variation of the SC parameters. The discrete optimization problem was solved using the same methods and under similar initial conditions. The loading of soft containers was carried out in a single layer. Figure 2 clearly illustrates the trends in the variation of the optimal values of the main parameters of soft containers.

Using the dependency graphs obtained from solving the optimization problem, it is possible to determine the optimal SC parameters (side width and height) that ensure the most efficient utilization of the vehicle payload capacity with given cargo compartment dimensions when transporting bulk cargo of a specified bulk density.

Figure 3a shows the graph $b^{opt} = f(h)$ of the dependence of the SC side width on its height for the case of transporting cargo with a bulk density γ_k = 0.65 t/m^3.

The graph indicates that, under the specified transportation conditions, the dependence $b^{opt} = f(h)$ is piecewise linear within certain ranges of the container height. In this example, within the height intervals $h \in$ [0.95 m to 1.00 m] and $h \in$ [1.15 m to 1.20 m], the optimal values of the parameter b change abruptly.

A similar behavior is observed for the corresponding dependencies $b^{opt} = f(h)$ at other values of bulk density of the transported material. Thus, Figure 3b includes a graph of an analogous dependence $b^{opt} = f(h)$ for the case of transporting cargo with a bulk density γ_k = 0.8 t/m^3. This graph also demonstrates characteristic "jumps" in the optimal values of the parameter b within certain ranges of variation of the container height h.

It should be noted that for relatively small values of the height h, under the selected initial data and parameter constraints, the objective function does not reach its maximum value, which is equal to the payload capacity of the selected vehicle. For the graphs in Figure 3a, this corresponds to the interval $h \in$ [0.7 m to 0.95 m], and for Figure 3b to the interval $h \in$ [0.7 m to 0.75 m].

Under these conditions, in the presence of significant deformation of the soft container, the wall width of which falls within these ranges, the optimal ratio between the height h and the wall width b may be violated in practice. This results in incomplete loading of the vehicle, i.e., inefficient transportation. This effect is particularly pronounced when the parameter b is selected close to the boundaries of the specified height h intervals without accounting for the possible deformation of the soft container.

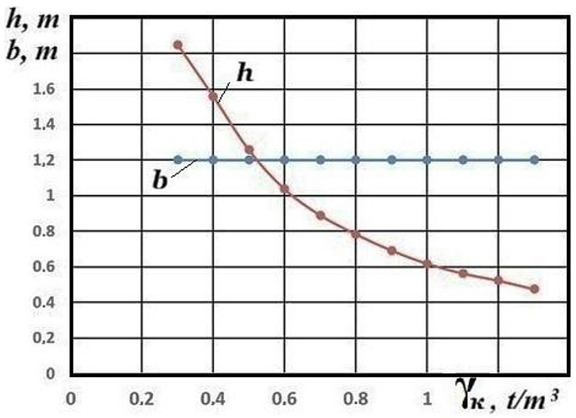


Figure 1. Graphs of the dependencies $b^{opt} = f(\gamma_k)$ and $h^{opt} = f(\gamma_k)$

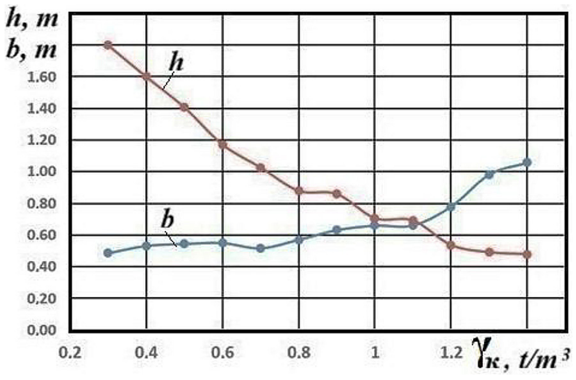
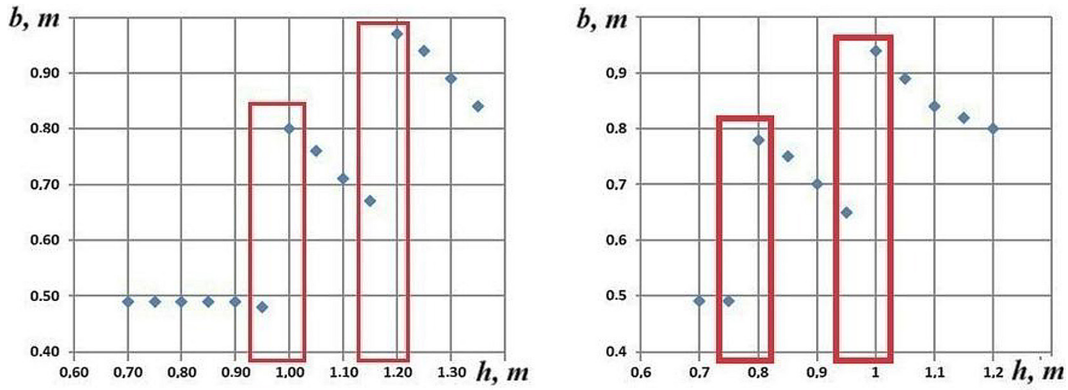


Figure 2. Graphs of the dependencies $b^{opt} = f(\gamma_k)$ and $h^{opt} = f(\gamma_k)$



a) b)

Figure 3. Graphs of the dependences $b^{opt} = f(h)$: a) $\gamma_k = 0.65$ t/m^3, b) $\gamma_k = 0.8$ *t/m*^{3}

Soft containers with a parallelepiped shape deform under the influence of bulk material somewhat differently compared to cylindrical ones [8]. Initially, their cross-section is a regular square with equal straight sides. Under the action of hydrostatic pressure exerted by the cargo, the container walls bulge outward, while the corners remain relatively rigid. As a result, the square cross-section in the middle part of the SC is transformed into a rounded square with an increased area.

A detailed investigation of the complex patterns of deformation of soft container shells is not the objective of this study. In authors' opinion, the most appropriate approach for describing these processes is based on the Janssen theory [51]. This theory makes it possible to determine the distribution of vertical pressure of bulk material in silos, containers, and other similar receptacles.

Unlike liquids, in bulk materials the pressure does not increase continuously with depth but reaches a certain saturation level. This is explained by the fact that part of the vertical load is transferred to the walls of the container due to friction forces between the cargo and the shell. In this case, part of the weight of the cargo is "supported" by the container walls, which leads to the SC walls bulging outward in their middle part. For flexible shells of soft containers, such a pressure distribution causes a characteristic deformation, in which the maximum expansion occurs in the middle part of the walls.

The deformation is greatest in the central part of each wall and minimal near the corners. This results in:

- an increase in the effective wall width of SC;
- a slight reduction in container height (due to volume conservation);
- the formation of bulges on the walls, which complicates the dense placement of a given number of containers in vehicle cargo compartments.
- The magnitude and shape of deformation of a loaded SC are influenced by several factors, the main ones being:
- the bulk density of the cargo γ_k,
- the height of the material column in the container h,
- the elastic modulus of the container material E (for woven polypropylene, the value of E significantly depends, for example, on the direction of load application-warp or weft-as well as on the weaving density, fiber type, etc.),
- the fabric thickness and the presence of reinforcing elements and lifting loops.

The characteristics of the SC deformation process can be described mathematically as follows.

1. To determine the cargo pressure at height z, one can use the classical Janssen formula [14], which allows determining the vertical pressure in a filled container:

$$p(z) = \frac{\gamma b}{2\mu k}\left(1 - e^{\frac{-2\mu k z}{b}}\right) \quad (8)$$

where: $p(z)$ – pressure in the middle of the SC at a depth of z, γ – specific gravity of the bulk cargo, N/m^3, b – container width, μ – coefficient of friction between the cargo and the SC wall, k – coefficient of lateral pressure (ratio of horizontal and vertical stresses).

2. The relative stretching of the material of the MC walls obeys the linear Hooke model for small deformations:

$$e(z) = \frac{p(z)}{E} = \frac{\gamma b}{2\mu k E}\left(1 - e^{\frac{-2\mu k z}{b}}\right) \quad (9)$$

3. The size of the deformed side of the MC cross-section at depth z:

$$b_d(z) = b_0(1 + e(z)) \tag{10}$$

4. Changing the height of the container (for reasons of preserving its volume):

$$h_d(z) \approx h_0 \frac{b_0^2}{(b_d(z))^2} \approx h_0\big(1 - 2e(z)\big) \tag{11}$$

The magnitude of the maximum transverse deformation of the soft container width $2e(z/2)$ is determined by a combination of several factors. The key ones include the properties of the bulk material, the geometric parameters of the container, and the mechanical characteristics of the shell material.

The most significant influence is exerted by the container size: as its height and side width increase, lateral expansion becomes more pronounced. The bulk density of the material also plays an important role, since heavier cargo generates higher internal pressure. In addition, the deformation is affected by the coefficient of friction between the cargo and the SC walls, as well as by the ratio of horizontal to vertical pressure, which determines the magnitude of lateral loading acting on the shell.

The properties of the shell material also make a considerable contribution, including its strength, stiffness, thickness, fiber structure, and the presence of reinforcing elements. The condition of the fabric may change under the influence of operational factors such as humidity, temperature, and prolonged loading (creep phenomena).

The final shape of a loaded soft container is also influenced by external conditions, including the packing density of containers within the vehicle body, pressure from adjacent containers, and dynamic loads arising during vehicle motion.

The calculated values of the deformation magnitude $e(z)$ are relatively small; however, under real conditions (taking into account multilayer effects, bulk density and filling degree of SC, as well as the condition of the shell material), it may reach 3 to 7%. For clarity, a graphical illustration of SC deformation under the influence of the loaded cargo is shown below (Figure 4).

On the left, the undeformed (unloaded) SC is presented as a parallelepiped with straight, flat walls and a square base. On the right, the deformed SC is depicted, with wall bulging directed outward under the action of internal pressure from the bulk material. The deformation is greatest in the middle part of each wall of SC and minimal near the corners (which remain relatively rigid due to the lifting loops). The maximum bulging is observed in the central regions of the side walls of SC. Due to this, the number of soft containers that can be placed along the width or length of a certain cargo space may decrease. In this case, there is a need to adjust the conditions of the optimization problems considered above.

Thus, the objective function of the optimization problem (5) considering the deformation of the shell SC will have the form:

$$G_{ijk} = f(N_{\text{i}}, M_{\text{i}}, Z_{\text{i}j}, (b_0 + 2e)_i^2, h_0(1 - 2e)_j, \gamma_k) \rightarrow G_B^{max} \tag{12}$$

Figure 4. Graphical illustration of SC deformation

Besides, expressions (3) will have the following form:

$$N_i = \left[\frac{B}{(b_0 + 2e)_i}\right], M_i = \left[\frac{L}{(b_0 + 2e)_i}\right],$$
$$H_j = \left[\frac{H}{(h_0 - 2e)_j}\right] \quad (13)$$

As already noted, the purpose of the article was to clarify approaches to solving optimization problems for choosing rational parameters of soft containers, which have the shape of a parallelepiped, in the cargo compartments of vehicles. Therefore, a detailed analysis of the physical mechanisms of SC deformation was not carried out in the work. Only certain fixed maximum values of the possible transverse deformation of the container were used in the calculations. Thus, Figure 5 shows the dependence $b^{opt} = f(h)$ graphs obtained when optimizing the objective function (12) considering the constraints (13) at the value of the maximum transverse deformation $2e$ = 7%. Comparison of the graphs presented in Figures 3b and 5 shows that taking into account the possible deformation of the shells of soft containers when solving the problems of optimizing the SC parameters to increase the use of the carrying capacity of vehicles allows obtaining more substantiated results.

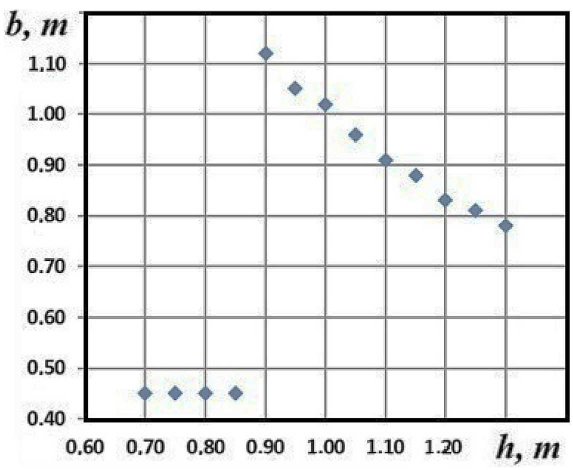


Figure 5. A graph of the dependency $b^{opt} = f(h)$: (γ_k = 0.8 t/m^3, $2e$ = 7%)

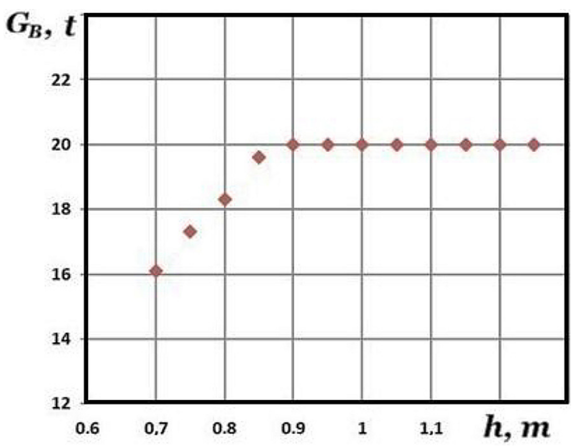


Figure 6. A graph of the dependency $G_B = f(h)$: (γ_k = 0.8 t/m^3, $2e$ = 7%)

With the selected initial data and parameter restrictions for the range of values $h \in$ [0.7 m to 0.9 m], it was not possible to achieve the extreme value of the objective function (12) due to the restrictions on the SC parameters adopted during the calculations and the scheme of loading containers in only one tier (Figure 6).

Thus, the solution of the specified optimization problems will allow selecting values of parameters b_i and h_j for soft containers in accordance with the dimensions of the selected cargo space and the given bulk density γ_k of the transported cargo, considering a possible deformation of the containers themselves. The specific value of the maximum deformation $2e$ is recommended to be determined either according to the results of experimental studies or by special engineering calculations.

Owing to the proposed approach, it is possible to achieve the most efficient use of the carrying capacity and capacity of vehicles, which will allow reducing the costs of transporting bulk cargo, while maintaining all the advantages of container technologies.

CONCLUSIONS

The use of soft containers for transporting bulk cargo is one of the promising ways to increase the efficiency of transport and logistics processes. Soft containers, which have the shape of a parallelepiped, have become widespread due to their simplicity of design, ease of manufacture and ease of operation.

Under the influence of the mass of bulk cargo, SCs, as a rule, undergo deformation, losing their ideal geometry. The most characteristic of this is the deformation in which the greatest expansion of the container shell occurs in the middle part along its height. The magnitude of the maximum transverse deformation depends on a complex of factors, in particular on the properties of the bulk cargo itself, the geometric dimensions of the container and the mechanical characteristics of the fabric from which its shell is made.

To ensure a more complete use of the carrying capacity and capacity of vehicles when transporting bulk materials in soft containers that have the shape of a parallelepiped, proposes approaches to solving optimization problems regarding the justified choice of optimal parameters of soft containers, taking into account the real geometry of the container, the parameters of the bulk cargo and the characteristics of the vehicle's cargo space. The use of the proposed approaches to solving optimization problems makes it possible to determine rational parameters of soft containers, which will reduce the overall logistics costs when transporting bulk cargo in soft containers.

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