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IMPROVING SAFETY CRITERIA FOR TRANSPORTING HAZARDOUS GOODS BY ROAD THROUGH OPTIMIZING THE GEOMETRIC PARAMETERS OF THEIR STOWAGE

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The object of research is the process of cargo transportation by road. The problem of efficient loading and securing of hazardous goods in box containers during their transportation by road is considered.

The basic principles of the voxel-based interpretation of the model of loading box containers on road transport are presented, and a general principle for calculating the fractal dimension of such three-dimensional objects has been developed. The calculation is based on the procedure of reducing the dimensionality of space by cutting the object into separate layers and determining the fractal dimensionality of two-dimensional slices. The proposed principle could be used to estimate the fractal dimension of three-dimensional objects in practical tasks in any industry.

A method for simplified calculation of fractal characteristics of three-dimensional bill of lading models of cargo stowage has been devised. The method is based on the assessment of the quality of blocking of the constituent elements of the spatial system in three coordinate directions by the fractal dimension of two-dimensional images of their frames. The method provides opportunities for calculating the quantitative characteristics of the quality of cargo stowage from the standpoint of its transportation safety.

A method for fractal stowing of goods in box containers on a truck platform has been proposed. This method of fractal stowage provides for the absence of slippage and displacement of boxes in the package and makes it impossible for them to overturn in extreme situations. The use of the fractal stowage method allows for an efficient and low-cost technology of securing the cargo as it involves only a circular bandage of the top layer of the loaded package of boxes and its fastening to the vehicle platform at four points

Keywords: road transportation, voxel-based stowage model, fractal dimensionality, cargo fastening, transportation safety

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1. Introduction

Currently, the situation in the European economy is characterized by the rapid development of integration processes, and therefore by the intensification of trade flows. This, in turn, had a significant impact on the rapid growth of transport services, which became peculiar and has its own specificity since the lion's share of cargo transportation within the EU is carried out by road transport. In order to ensure the competitiveness of business entities as market participants in the provision of transport services, there is a need to establish new, higher requirements for the organization of the transportation process, as well as related services [1]. In particular, such innovations are aimed at creating conditions for ensuring the safety of transported goods.

The solution to this problem, at first glance, seems elementary. The cargo, in order to preserve it, should be properly placed in the rolling stock, secured, subject to timely delivery in compliance with all established requirements, including transportation safety, and unloaded. The safe transportation and preservation of goods is a problem that business entities do not solve comprehensively but only try to eliminate individual shortcomings when solving specific tasks to enable commodity flows [2].

One of the main factors affecting the preservation of goods is their correct placement and fastening. If we consider the transportation of goods by road transport on the territory of EU countries, it can be noted that the emphasis is on the quantity of transported goods, and not on its preservation and the integrity of the delivered goods. Poorly secured cargo and its incorrect placement are often the cause of traffic accidents, even on safe sections of the road. The transportation of hazardous goods (HG) is accompanied by additional risks as they can cause explosions, fires, death, and injury to people, and can also cause significant material damage and damage to the environment [3].

In order to prevent accidents during the transportation of hazardous goods by various types of transport, national authorities in many countries for a number of years have regulated such transportation with the help of fixed legislative norms and rules [4]. The European Agreement on the International Carriage of Hazardous Goods by Road (DPA) [5] became the main document regulating the transportation of hazardous goods by road. One of the key clauses in the agreement is an article dealing with the problems of loading, blocking, and securing HG.

The modern standard methods of securing cargo include cargo locking; fastening by pressing; fastening with a loop; fastening with stretch marks; connection («spring», circular); a combination of several of the above.

A critical analysis of the above-mentioned fastening methods revealed that they are quite costly and time-consuming. The process of loading and locking cargo in containers is too individual and chaotic according to technological requirements and requires experience, special qualifications, and knowledge from specialists.

As a rule, the use of only standard fastening techniques cannot fully guarantee the safety of transportation and maximally exclude provoking emergencies on the road (shifting, sliding, overturning of cargo). At the same time, the processes of planning the loading and fastening of HG are not considered as an interrelated set of tasks from the standpoint of manufacturability, economy, and safety of their transportation.

Therefore, the issue of improving one of the main elements in the process of transporting hazardous goods by road transport, namely the set of loading operations, is relevant. This element, during transportation, has the greatest impact on safety indicators, and research into the optimization of the processes of HG stowage, blocking, and effective fastening is interesting from a scientific point of view.

2. Literature review and problem statement

Our review of the literature related to the above issues involved the following directions: features of the requirements for the transportation of heavy goods vehicles by road transport; innovative techniques of stowing, blocking, and fastening of HG; the influence of the geometric parameters of three-dimensional objects on the methods of their dense arrangement in a limited three-dimensional space; the use of fractal geometry methods to improve the technological qualities of researched objects and processes.

Work [6] shows that in the process of transporting unsecured cargo, a change in the speed or direction of movement of the vehicle can lead to abnormal situations. The greater the deviation of the car from straight and uniform movement (during sharp braking, acceleration, turns, lane changes, etc.), the more force the load will exert on the car platform. Such an unsecured load is kept from shifting only by the force of friction. The paper notes that, in practice, one friction force is not enough to prevent the movement of loads. The reason is the possibility of vertical shifts of loads in the process of dynamic movement of the vehicle. They are caused by the poor condition of the roads and reduce the effect of the existing frictional forces, up to their complete disappearance. However, no specific recommendations have been provided to eliminate the above problem for cargoes that are made up of multiple components in one monolithic package. This problem of the safe transportation of packaged cargo could be solved only if it was necessarily blocked and secured.

In paper [7], methods for stowing individual components of «box» cargo in a container are proposed. Limitations that may affect the quality of the loading process are classified. Heuristic and exact approaches to stowing individual elements in a limited three-dimensional space are considered. However, the process of stowing the constituent elements cannot be used in this work since in [7] the authors are talking only about idealized both the elements and the container itself. That is, the proposed algorithms do not take into account any of the limitations noted in [7]: volume and weight; restrictions related to the geometric characteristics of the package; restrictions on the orientation of its constituent elements; restrictions on contracting; restrictions on the positioning of each of the «boxes».

In [8], it is stated that when transporting hazardous goods by road transport, additional requirements are put forward for the securing of goods, primarily related to the increased danger of their transportation. As an option for solving the problem, the paper proposes additional elements of HG fastening with the help of appropriate means capable of holding loads on a moving car platform without guaranteed movement, overturning, and without the possibility of damage to their packages. However, such additional work on fastening HG requires a significant increase in financial costs and time for loading operations.

Mechanisms for securing hazardous goods to prevent sliding, overturning, and rolling should be developed exclusively in accordance with regulatory documents. In study [9] it is indicated that the following factors must be taken into account for the effective development of cargo fastening schemes: the direction of fastening; fastening methods and means; friction; dimensions and center of gravity; mass of the cargo. All of the above factors are too subjective in practical application, and their implementation directly depends on the qualifications of loading operations specialists.

Road transport suitable for transporting heavy goods vehicles is very sensitive to the location of the center of gravity of the cargo. The problems of its influence on safety are considered in work [10], which states that the maximum payload can be used only if the center of gravity is located within a certain interval. However, practical recommendations for solving the problem of effective displacement of the center of gravity due to the formation of special loading schemes are not given in the work. One of the options for solving such a problem may be an approach to completely block individual cargo elements in a single monolith.

In the recommendations by the European Commission [11], a classification of cargo fastening techniques is proposed, which include blocking; fastening by pressing; fastening with a loop; diagonal fastening; fastening with stretch marks; direct communication; a combination of several methods together with friction. However, the requirements for their use in the case of transporting HG on automobile platforms have not been formulated.

One of the problems of transporting heavy goods is the development of effective schemes for loading them onto platforms and blocking individual elements. The geometric parameters of cargo stowage are of decisive importance. Algorithms for stowing irregular 3D objects into a cuboid of minimum volume are considered in [12]. They are based on the principles of non-overlap limitation. However, the above optimization problem of stowage cannot be used in the process of loading HG. The reason for this is the possibility of continuous movement and rotation of individual objects, which form the basis of the proposed algorithms.

Paper [13] considers the algorithms developed for solving the problem of placing orthogonal polyhedra in a container. The «potential containers» model is used to describe all free areas of a container with a complex geometric shape. This model is based on the application of intersection operations to obtain areas of permissible placement of each considered object of a complex geometric shape. However, the application of these algorithms in the development of schemes for loading HG into a container do not meet the requirements for a comprehensive approach to stowing, blocking, and fastening. All of this gives reason to assert that the choice of the most effective option for loading a vehicle onto a car platform depends on the geometric configuration of the components of the load and the nature of their possible movements during transportation.

No works reporting the analysis of the complex influence of the geometric characteristics of the elements of packaged goods on the technological, economic and safety criteria of transportation were found. Fractal characteristics were not used to solve the problem of the relationship between the quality of loading operations and the blocking and fastening of individual package elements.

At the same time, the literature [14, 15] proposed ways to find fractal geometric characteristics of sets of pixels in two-dimensional space. These techniques involved the segmentation of binary images of specific objects according to a number of geometric features. These included the possibility of topological identification of each characteristic area [16], the procedure for determining the fractal dimension of both individual segments and the image as a whole. An analysis of the intensity of influence of the above calculated parameters on improving the functional quality of the models was carried out, and recommendations were devised on the basis of it to optimize the technical and technological characteristics of these physical objects. However, fractal characteristics of three-dimensional images in three-dimensional space were not considered.

Our review of the above literary sources revealed that there is no comprehensive consideration of all stages of loading operations for HG, from the process of stowing to fastening; no techniques of fastening individual classes of HG were reported; the fractal characteristics of cargo stowage were not considered as the main element of assessing the safety quality of transportation of HG by road transport.

3. The aim and objectives of the study

The purpose of our study is to improve the safety, technological, and economic indicators of the transportation of hazardous goods by optimizing the geometric parameters of their stowage. Stowage is based on a fractal approach to blocking multiple individual packages from shifting, sliding, and overturning. This will make it possible to increase the safety of transportation of HG, simplify the technology of loading operations and reduce their cost.

To achieve this goal, the following tasks are set in the work:

– to devise a general principle of calculating the fractal dimensionality of voxel models of objects for a limited area of three-dimensional space;

– to develop a method of simplified calculation of the fractal dimensionality of voxel models using two-dimensional projections of their frames;

– to propose a technique for the fractal stowage of hazardous goods with complete blocking of constituent elements.

4. The study materials and methods

The object of our research is the process of transporting goods by road transport, namely such an element as the technology of loading, locking, and securing hazardous goods in box containers on car platforms.

In modern technologies for modeling real objects or processes, innovative approaches based on the analysis of the geometric parameters of these objects and their influence on the quality of technological and structural properties are increasingly common. At the same time, classic geometric images are actively expanded with images of a complex shape with non-integer dimensions and an irregular structure. The most obvious examples of such objects are the structure of the earth and water surfaces, the vegetation cover of the land, the human cardiovascular system, types of porous materials or the roughness of the surfaces of metal products, transport routing schemes of cities, etc. The application of methods, algorithms, and basic forms of classical geometry to adequately represent the models of the above objects is time-consuming, and in many cases simply impossible to implement [17]. Such «chaotic-cut» structures are identified as fractal, multifractal, or quasi-fractal images.

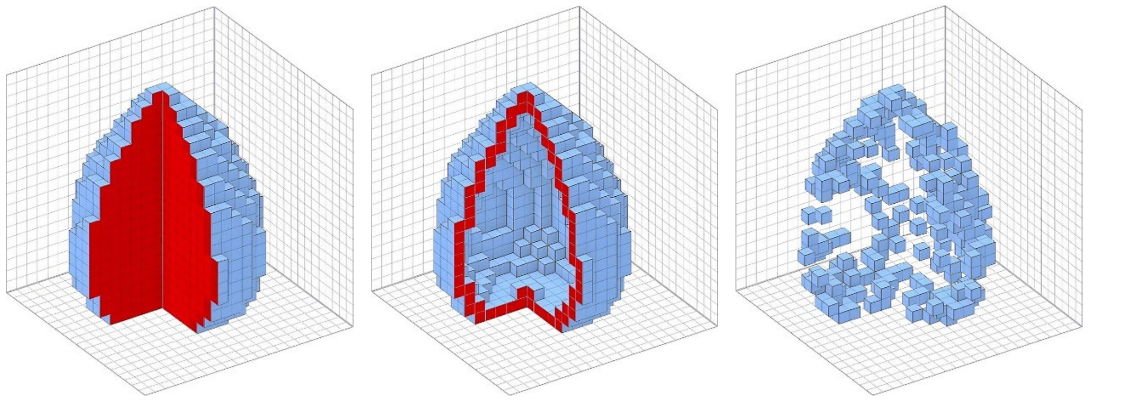
Fractal theory is already developed quite well, in principle it is able to cope with the given problem. However, the methods of its implementation are time-consuming, often separated from the comprehensive understanding and identification of the basic geometric characteristics of the modeled objects. At the same time, the practical application of algorithms for calculating fractal characteristics is implemented only for one- and two-dimensional structures. If such characteristics are calculated and analyzed on the basis of two-dimensional images of real objects and sets, then they usually have a discrete-pixel structure.

In order to generalize the necessary information about objects in images and use it to solve specific tasks, it is necessary to have procedure and algorithms for calculating the main characteristics of objects. These include Euclidean and fractal dimensionalities, shape parameters, geometric structure and composition of objects, other geometric properties. On the basis of the analysis of the found characteristics, the conclusions about the types of objects, the quality of the investigated image are summarized in terms of determining directions for improvement of its technical and technological properties.

One of the defining geometric characteristics of images of natural and physical objects is their fractal dimensionality [18]. It is the fractal dimensionality (along with other geometric characteristics) that can become the basis for effectively improving the properties of the model first, and later, accordingly, of real objects.

However, modern technologies and visualization tools are increasingly improving, sometimes requiring the presence of images of models in spaces exceeding 2 dimensions, and therefore require the development of new methods and approaches for determining geometric characteristics.

An alternative to representing objects, including fractal ones, within the framework of solving this problem of fractal stowage of loads is a certain space filled with elementary volumes – voxels. The theoretical principles of identification and separation of fractal geometric characteristics of voxel models are given in [19]. It is noted that voxels are a kind of analog of pixels in two-dimensional graphics. Each voxel is usually implemented as a cube (Fig. 1).



a *b* *c*

Fig. 1. Voxel models: *a* — three-dimensional body; *b* — surface; *c* — an unordered set of points

The main disadvantage of such representation of images with different topological or fractal dimensionalities is their physical size. For example, a volume with an average resolution of 256^3 requires about 16 million voxels to be stored. To generate an image of a 3D object on the screen, they must all be processed.

However, the volume has a number of important advantages: it can provide information about the geometric characteristics of the internal elements of the model, and not only the outer layer. In addition, voxel models make it possible to visualize highly detailed objects without using additional software resources to identify information about the type of material, density, elasticity, and other characteristics.

A model of a discrete image of a three-dimensional space given by a set of voxels can be cubic lattices, which are formed by the intersection points of three mutually perpendicular families of parallel lines with a distance between them equal to the scale unit – *unit*. A value equal to, for example, the size of a pixel on the projection of a voxel image of a geometric object can be chosen as a unit.

Geometric identification of voxel models of objects makes it possible to fragment them according to a number of properties [20]. The main ones include topological dimensionality, geometric dimensions of the voxel model, shape parameters of a discrete image, static moments of given areas, and other geometric characteristics. All calculated parameters will indirectly affect the technical and technological properties of objects modeled in practical tasks.

Another defining characteristic for the given tasks is the fractal dimensionality of the images, which requires special attention because fractal objects whose dimensions do not exceed the dimensionality of the space can be placed in each Euclidean space of a certain dimension.

As defined above, a single fragmentation element, be it a pixel, voxel, or hypervoxel, is a point model with classically defined dimension 0. An infinite set of such individual, independent fragmentation elements with 0-dimensional dimensionality of each element can represent a fractal set with fractional dimensionality D_0. Thus, when placing an infinite set in a two-dimensional space (pixel model), the value D_0 is within $0<D_0<2$. When placed in E^3 (voxel model) – $0<D_0<3$. Generalizing for the space E^n, it can be stated that it is within $0<D_0<E^n$.

In a similar way, it is possible to determine the limits of the fractal dimensionality of discrete models of lines D_1. Such geometric objects with certain properties may have a fractal dimensionality in the range: $1<D_1<E^n$.

Fractal surfaces D_2 in Euclidean spaces of different dimensionalities have, respectively, the dimensionality $2<D_2<E^n$. It should be noted that in this paper only modifications of sets of classical geometric objects were considered.

Accordingly, the main hypothesis of this study assumed the possibility of devising a new technique for the fractal stowing of box containers as spatial voxel elements in a limited three-dimensional space. To this end, the task of developing the basic principles of calculating the fractal dimensionality for voxel-defined objects is set. Due to the analysis and management of the fractal characteristics of such spatial structures, as part of the research problem, it would be possible to significantly improve the quality of blocking the package elements, which means to minimize the costs of cargo tying.

5. Results of investigating the influence of fractal dimensionality of the voxel model of a cargo on the technology of its stowing and fastening

5. 1. General principles for calculating the fractal dimensionality of voxel models of objects

The principle of calculating the fractal dimensionality of the voxel model of a three-dimensional object was based on the immersion of a connected or disconnected set of voxels in a defined volume of space E^3.

To measure the volume of a given object with fragmentation α, an elementary voxel with a side of *unit*, i.e., an elementary cube with a volume of $\Delta\times\Delta\times\Delta=\Delta^3$ (where Δ=*unit*) is taken. *N* pieces of such elementary voxels were selected for the volume coverage of the object, from which the volume was determined using the expression:

$$V = N_{(\Delta)} \times \Delta^3 = C \times \Delta^{3-D}. \quad (1)$$

Omitting the undefined factor *C* in the classical expression $N=C\times\Delta^{-D}$, for any iteration of scale invariance *n*, we defined:

$$V_n = \left(\frac{N_{(\Delta)}}{\alpha^3}\right)^n, \ \Delta_n = \left(\frac{1}{\alpha}\right)^n, \quad (2)$$

or:

$$\left(\frac{N_{(\Delta)}}{\alpha^3}\right)^n = \left(\frac{1}{\alpha}\right)^{n(3-D_3)}.$$

By logarithmizing the last expression, the following is obtained:

$$3-D_3=\frac{\ln\left(\dfrac{N_{(\Delta)}}{\alpha^3}\right)}{\ln\left(\dfrac{1}{\alpha}\right)},$$

$$D_3=3+\frac{\ln\left(\dfrac{N_{(\Delta)}}{\alpha^3}\right)}{\ln(\alpha)}=\frac{3\ln(\alpha)+\ln\left(\dfrac{N_{(\Delta)}}{\alpha^3}\right)}{\ln(\alpha)}=\frac{\ln\left(N_{(\Delta)}\right)}{\ln(\alpha)}. \qquad (3)$$

Expression (3) became the basis for calculating the fractal dimensionality of the object represented by the voxel model. However, the practical calculation of the number of elementary cubes in a whole series of large-scale iterations of finding the fractal dimensionality of the voxel model according to (3) has become a time-consuming procedure. It was proposed to introduce a layer-by-layer calculation of the fractal dimensionality of the constituent elements by switching to a set of pixel models. Then the procedure for calculating the dimension of the voxel model was reduced to the expression:

$$D_3=1+\frac{\ln\left(\dfrac{1}{\alpha}(N^1_{(\Delta)}+N^2_{(\Delta)}+N^3_{(\Delta)}+\ldots+N^{\alpha}_{(\Delta)})\right)}{\ln(\alpha)}, \qquad (4)$$

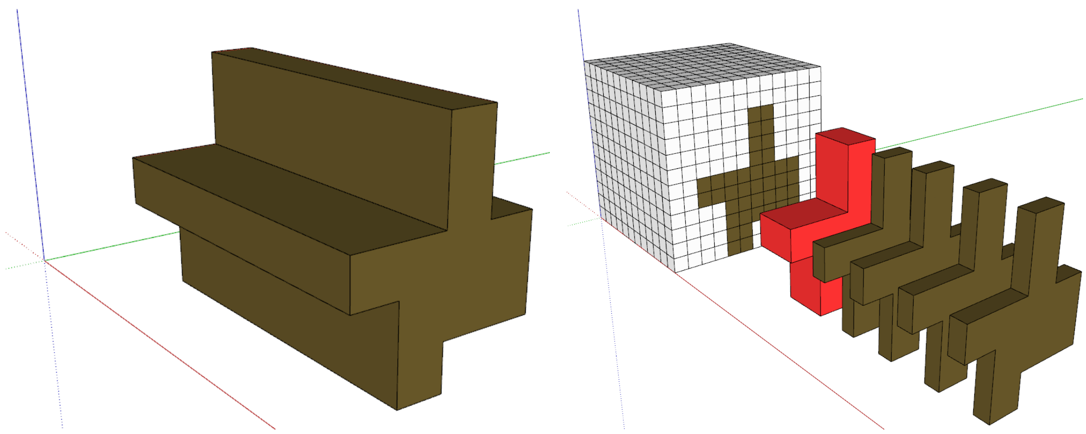
where $N^1_{(\Delta)}$, $N^2_{(\Delta)}$, $N^3_{(\Delta)}$, ..., $N^{\alpha}_{(\Delta)}$ is the number of occupied cells (pixels) in each of the layers.

Expression (4) made it possible to significantly simplify the procedure for calculating the fractal dimensionality by reducing the dimensionality of space for each layer of a given object with the determination of its required geometric characteristics. The practical implementation of expression (4) was carried out for the model of a body immersed in three-dimensional space (Fig. 2, *a*).

It was determined that when applying a set of large-scale coverings with cubes of the appropriate size with $\Delta\to 0$ of the given model, the fractal dimensionality tended to 3.

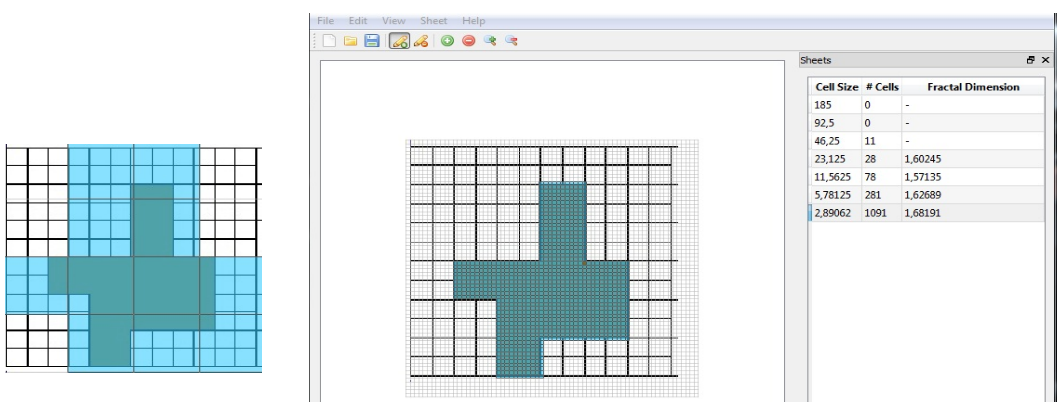
However, for clarity of operation of the proposed principle, iterations of a lower level of fragmentation with the index α were selected. At each stage of large-scale fragmentation, the given body was broken into separate layers of thickness α along the *x* axis. Each layer was cut by a median plane, thereby reducing the dimensionality of the space to two-dimensional (Fig. 2, *b*). Next, the well-known «FrakOut» program was used, which was applied to calculate the fractal dimensionality of each of the layers using the grid method.

Fig. 3, *a* shows an example of large-scale coverage of a given object with cells of a certain level of fragmentation is given, and Fig. 3, *b* – numerical values of the fractal dimensionality of the corresponding layer.



a *b*

Fig. 2. The principle of reducing the dimensionality of a solid object: *a* – an object in three-dimensional space; *b* – elements of fragmentation of the object



a *b*

Fig. 3. Calculation of the fractal dimensionality of the layer (two-dimensional object): *a* – covering with cells; *b* – fractal dimensionality of a certain layer

Using expression (4), the fractal dimensionality of the given body at the stage of large-scale fragmentation α=32 was calculated:

$$D_3 = 1 + \frac{\ln\left(\frac{1}{32}\sum_{1}^{n} 281\right)}{\ln(32)} = 2.63.$$

In the above example, all layers of a given body have the same fractal dimensionality. Therefore, the number of cells covering the section is 281, and α is the same in all layers of fragmentation. In the general case, the fractal dimensionality of each of the object fragmentation layers will have different numerical values.

5. 2. Technique for the simplified calculation of the fractal dimensionality of voxel models using projections of their frames

As a rule, in the practical application of fractal characteristics to improve the technological or technical properties of the studied objects, the accuracy of measuring the fractal dimensionality is not of key importance. Decisive are the trends or the trend of forecasting the impact of the numerical values of the fractal dimensionality on the qualitative indicators of the projected objects. This assumption made it possible to significantly simplify the practical implementation of the task of analyzing the effect of fractal dimensionality on the geometric characteristics of voxel-based models.

As an example, the unordered placement of two types of prismatic bodies in a prismatic container of certain sizes was considered: 6 blue cubes and 5 yellow prisms (Fig. 4, *a*). The bodies were immersed in the given space, placed chaotically but densely. The scale invariance of the voxel representation (Fig. 4, *b*) of this space allows us to determine the fractal dimensionality of a specific spatial structure. Using (4), its fractal dimensionality was calculated: D_3=2.323.

A simplified calculation technique involved the frame representation of its elements (Fig. 4, *b*) and determining their geometric characteristics separately on three orthogonal planes: *zOx*, *yOx* and *zOy* (Fig. 5).

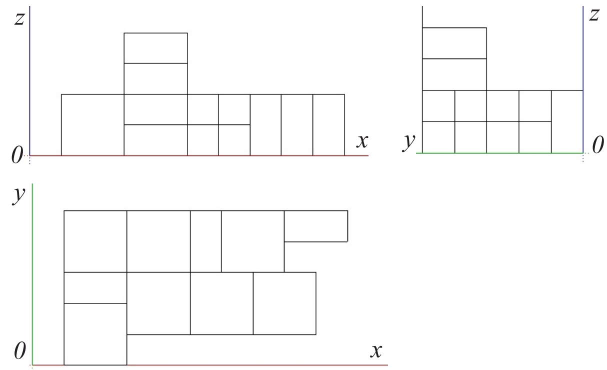
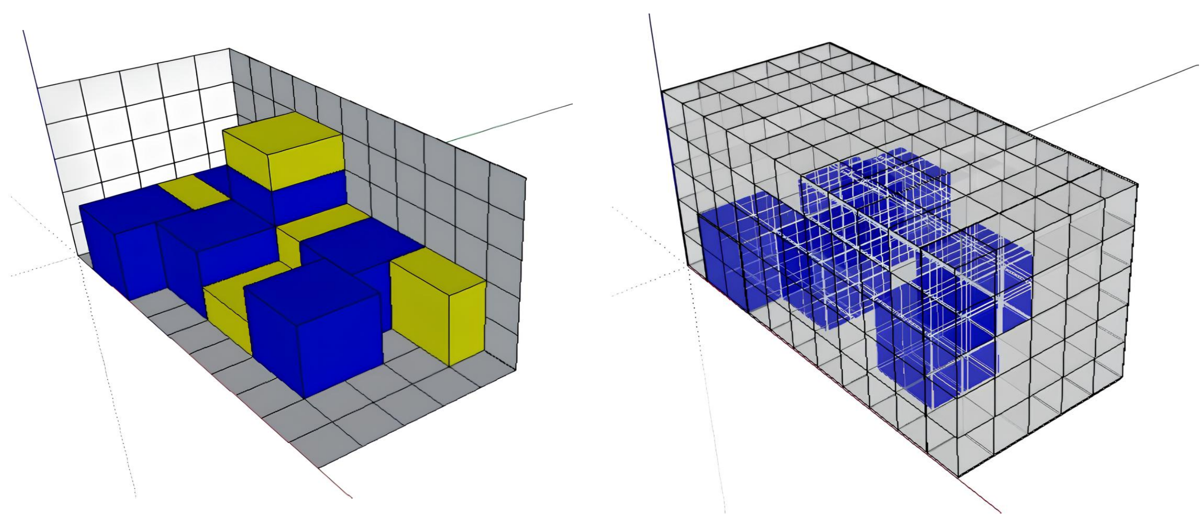


Fig. 5. Projections of the frame of the spatial structure on three orthogonal planes

Each element of the model, on each projection, is limited by 4 frame lines. The projection of a set of elements of the frame determines the fractal dimensionality of the two-dimensional image, and the mutual displacement of lines on the projections directly affected the value of the fractal dimensionality. With the help of the specialized program «Java Applet to Compute Fractal dimensionalities», the fractal dimensionality of the frame of lines of a set of prismatic bodies was calculated for each projection plane (Fig. 6).

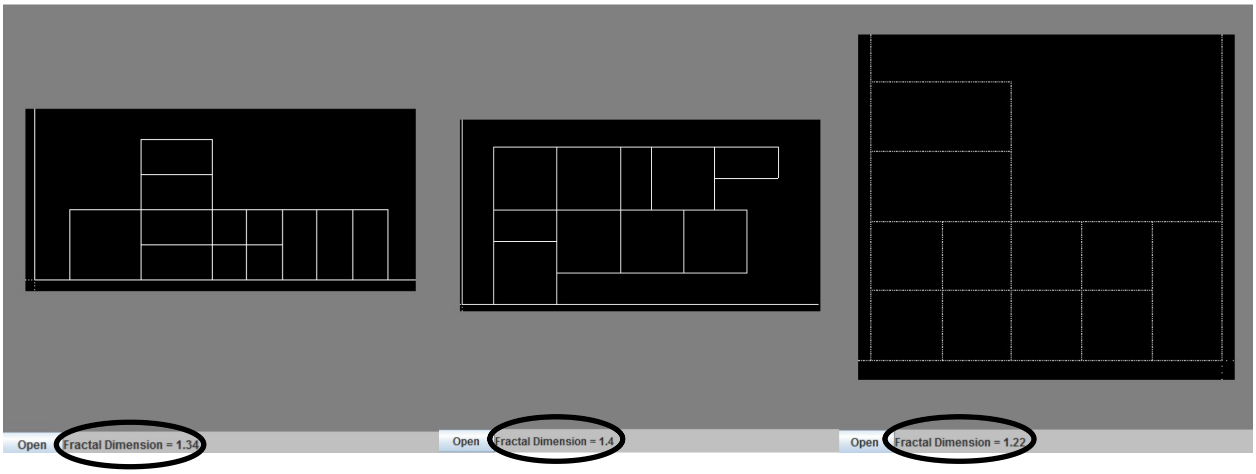
By rearranging individual elements in the container and shifting them relative to the three axes of the spatial coordinate system, the structure of the location of the objects was changed. An analysis was carried out of how the indicators of the fractal dimensionality of the images on the projections changed with different variants of displacement. Fig. 7 shows, as an example, a software calculation of the fractal dimensionality of the new model of the arrangement of elements in the *yOx* plane.

Analysis showed that the fractal dimensionality index increased from D_{yOx}=1.4 to D_{yOx}=1.5. Experimental studies of other types of possible displacements of elements in a closed space demonstrated that the maximum, for a given set of elements, fractal dimensionality of the image of the frame model on the *yOx* plane can be brought to the value D_{yOx}=1.57. In the same way, the values of the fractal dimensionalities of the frame on the projection planes *zOx* also increased from D_{zOx}=1.34 to D_{zOx}=1.42; on *zOy* from D_{zOy}=1.22 to D_{zOy}=1.38.



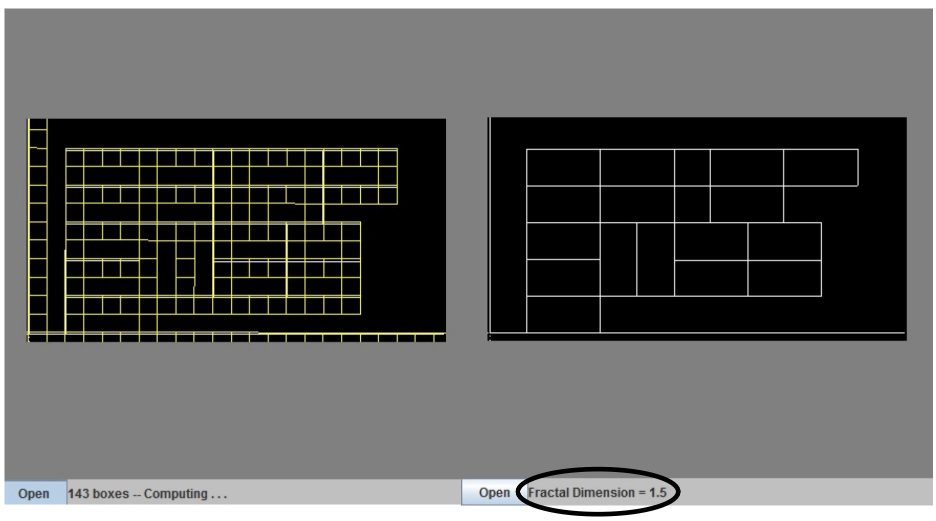
a *b*

Fig. 4. Two types of prismatic bodies in a container: *a* – unordered placement; *b* – scale invariance of the voxel representation



a *b* *c*

Fig. 6. Calculation of the fractal dimensionality of the set of framework lines of prismatic bodies for each projection plane: *a* – *yOx*; *b* – *zOx; c* – *zOy*



a *b*

Fig. 7. Fractal dimensionality of the corrected model of the arrangement of elements in the *yOx* plane: *a* – the level of fragmentation of the frame projection coverage; *b* – the resulting value of the fractal dimensionality of the frame

This property of dependence of the value of the fractal dimensionality of the frame projections of individual geometric elements on the intensity of their displacements relative to the axes of the coordinate system was used to devise a fractal technique for stowing HG for their safe transportation by road transport.

5. 3. Technique for the fractal stowage of hazardous goods with complete blocking of constituent elements

A new technique for stowing and securing multi-layer cargo in a box container with blocking from sliding and overturning of its individual elements is proposed.

For example, the need to transport 150 boxes measuring 500×500 mm in a car container with dimensions of 2700×6000×2200 mm was considered. The boxes contain pyrotechnic substances belonging to the 1st class of hazardous goods, which means that they require special attention to create safe transportation conditions.

As the simplest, i.e. reference, scheme of loading a given number of boxes from HG, the scheme of their dense stowage in three horizontally placed stacks of 50 boxes in each layer was adopted (Fig. 8).

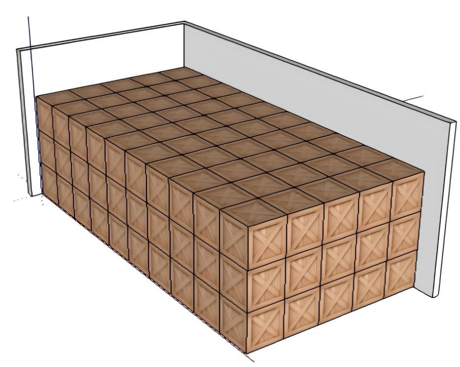


Fig. 8. The simplest scheme for loading boxes of the same size

The fractal dimensionality of the voxel model of such a reference scheme of stowage was calculated according to the technique described in chapter 5.2, through a frame representation of this cargo on three orthogonal projection planes (Fig. 9). Accordingly, the indicators of the fractal dimensionality were, in the *zOx* plane: D_{zOx}=1.72, in the *yOx* plane: D_{yOx}=1.75, in the *zOy* plane: D_{zOy}=1.33.

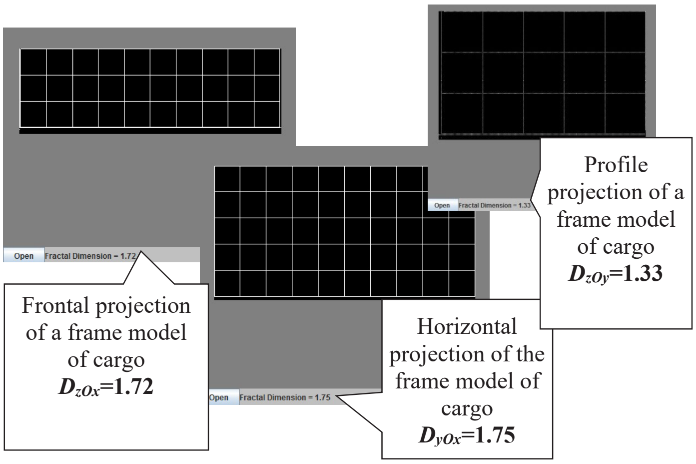


Fig. 9. Determining the fractal dimensionality of the frame representation of the cargo model on three orthogonal projection planes

The calculated values of the fractal dimensionality of the frame model on the projections are minimal since the two-dimensional images on the planes contain the minimum number of lines of the frame of the constituent elements.

These indicators of the fractal dimensionality on the projections show that in the single monolith of the packed cargo there is a complete lack of blocking of the constituent elements from displacement along all three axes of the spatial coordinate system. For the safe transportation of such cargo, designing special equipment is additionally required, which would ensure blocking and fastening of its individual vertical and horizontal layers. Such measures will require the carrier to spend significant material costs on additional equipment and a considerable amount of time to perform the work.

It is proposed to significantly reduce the costs of blocking individual cargo units and, as a result, to reduce the cost of the technological process of its fastening, by devising a new loading technique with a fractal stowage of its individual elements. The technique involves controlling the locking of boxes in stacks by changing the geometric characteristics of the loaded monolithic package. One of the defining geometric characteristics of the loading scheme of the constituent elements was the fractal dimensionality of the projections of the frame of the packaged cargo on orthogonal planes.

Assertion. To ensure effective geometric blocking of stacked containers in boxes with hazardous goods, the fractal dimensionality of the two-dimensional projections of the frame of each stack of the cargo package in the direction of one, two, or three axes of the spatial coordinate system of the container should be increased (relative to the reference). The reference value of the fractal dimensionality of the package (individual projections of the package frame), in this case, should be the simplest geometric scheme of stowing boxes (Fig. 8).

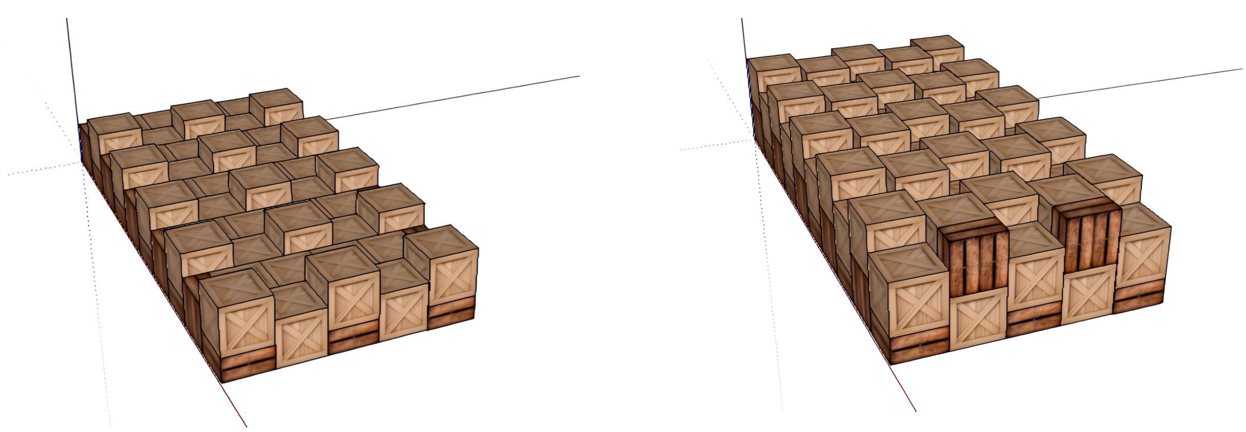
Using the above statement, an improved fractal stowage scheme of a homogeneous box container with a dangerous cargo was built. The scheme included both the container itself and interlocking pallets, modularly tied to the dimensions of the boxes.

Fig. 10, *a* shows the geometric scheme of loading the 1st layer of boxes, the maximum blocking of which is ensured by shifting individual elements of the container in the direction of the *x* and *z* axes. The scheme of the 2nd layer (Fig. 10, *b*) includes an additional displacement of the components of the package along the *y* axis.

This technique of stowing two layers of the container enabled 100 % blocking of the component elements from sliding and overturning caused by the possible action of inertial forces during the dynamic movement of the car platform. Further repeating the formation of cargo layers with locking elements, alternately shifting them relative to the axes of the spatial coordinate system (Fig. 11), a monolith of a package of boxes with improved (regarding locking) geometric parameters was obtained.

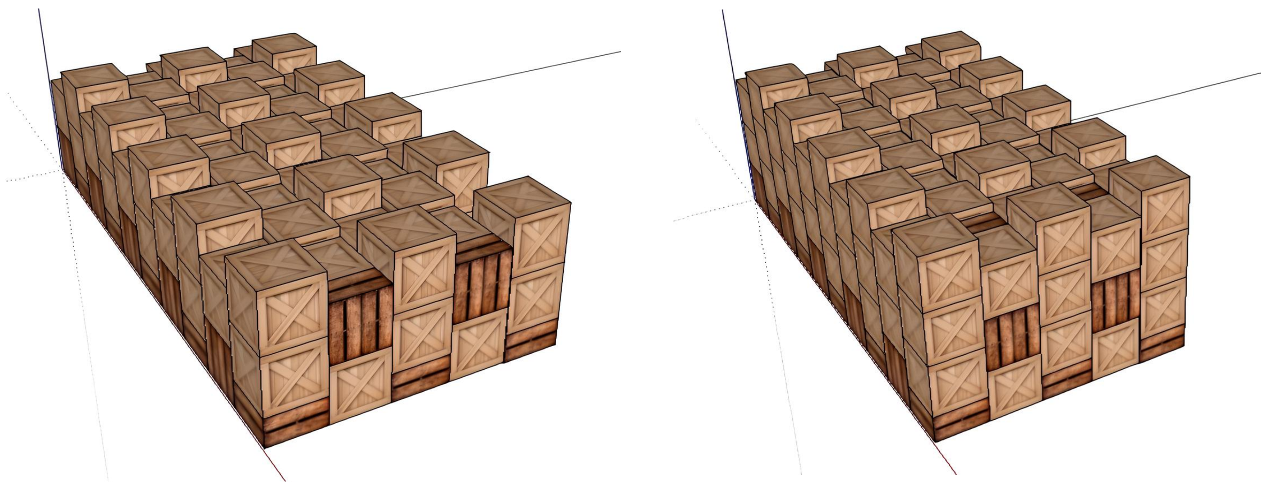
By shifting the elements along all three axes, the number of frame lines of the package on all projection planes automatically increased, which means that the numerical value of the fractal dimensionality of each two-dimensional image changed (Fig. 12).

Using the results from chapter 5.2 and the specialized program «Java Applet to Compute Fractal dimensionalities», it was determined how the indicators of the fractal dimensionality of individual projections of the formed package changed in comparison with the standard shown in Fig. 8. So, in the *zOx* plane, the fractal dimensionality acquired the value D_{zOx}=1.80, in the *yOx* plane: D_{yOx}=1.87, in the *zOy* plane: D_{zOy}=1.63 (Fig. 13).



a *b*

Fig. 10. Loading scheme: *a* — the first layer; *b* — the second layer



a *b*

Fig. 11. Stages in the sequential formation of layers of cargo elements with their complete blocking from movements in the spatial coordinate system: *a* – third layer; *b* – the fourth layer of the molded package

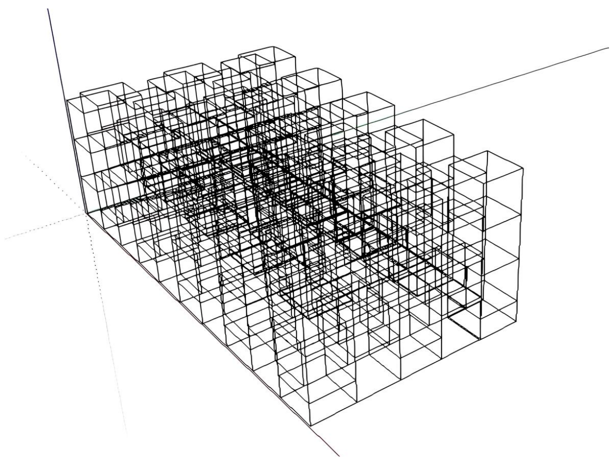


Fig. 12. Increasing fractal dimensionality by increasing the number of package frame lines

An increase in the numerical values of the dimensionality on all two-dimensional images of the model showed that the proposed technique of fractal stowing ensures complete blocking of the constituent elements from displacement relative to the three axes of the coordinate system.

6. Discussion of results of investigating the influence of fractal dimensionality of the cargo stowage model on the safety and cost of transportation

The research carried out as part of our work confirmed the relevance of devising a comprehensive approach to carrying out loading operations (schemes of stowage, locking, fastening) for the transportation of HG by road transport.

The devised technique for the fractal stowing of HG in box containers makes it possible to exclude any movement of cargo during the dynamic movement of the car platform, to reduce the quantity of equipment for tying packages, and to minimize the number of attachment points. This technique makes it possible to increase the safety of transportation of HG and significantly reduce the cost of loading and fastening operations.

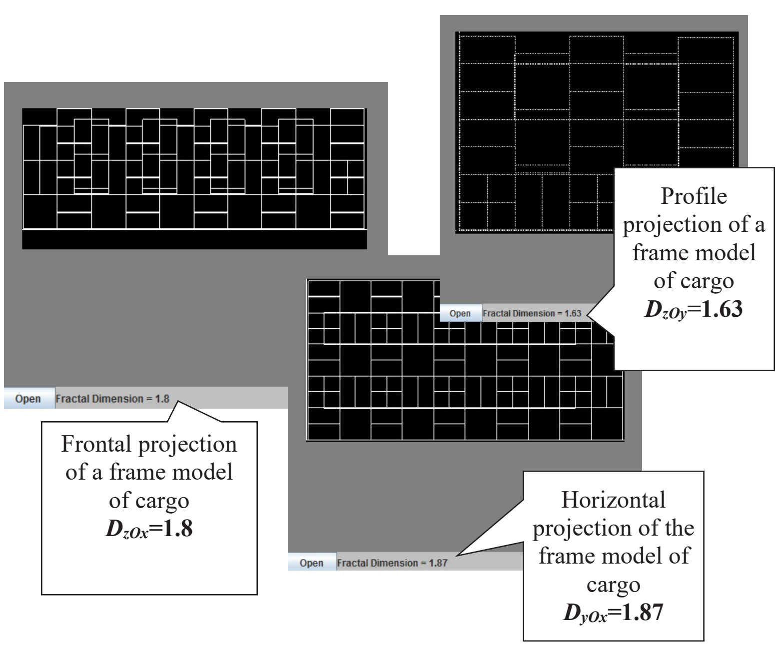


Fig. 13. Calculation of the fractal dimensionality of individual projections of the frame of the formed package

The proposed voxel model of the representation of cargo elements in a limited area of three-dimensional space (Fig. 1) made it possible to reveal the absence of methods for calculating the main, within the framework of the work, geometric characteristic of the formed spatial system – its fractal dimensionality. Therefore, in the work we have developed a general principle for calculating the fractal dimensionality of three-dimensional voxel-represented objects by reducing the dimensionality of the space in which they are immersed, with a comprehensive analysis of the geometric characteristics of each layer of the model (Fig. 2, expression (4)). The proposed principle could be applied to estimate the fractal dimensionality of three-dimensional objects in various practical tasks.

Since the fractal dimensionality of packaged cargo has become decisive for evaluating the efficiency of its stowage with the blocking of constituent elements, the paper proposes a technique for the simplified calculation of its numerical values for three-dimensional objects. This technique is based on the principle of reducing the dimensionality of the space for calculation and consists in evaluating the quality of the blocking of a set of elements in three coordinate directions by indicators of the fatal dimensionality of two-dimensional images of their frames (Fig. 5, 6).

A technique for the fractal stowing of HG in a box container on a car platform has been devised. The fractal diagram of stowage (Fig. 10, 11) confirmed the complete blocking of the elements of the package relative to the three axes of the spatial coordinate system. A test example of the formation of a package of boxes in a container of given dimensions showed that the values of the fractal dimensionality of its frame significantly increased on each of the projection planes (Fig. 13), in comparison with the standard (Fig. 9): in the zOx plane from D_{zOx}=1.72 to D_{zOx}=1.80, in the yOx plane from D_{yOx}=1.75 to D_{yOx}=1.87, in the zOy plane from D_{zOy}=1.33 to D_{zOy}=1.63. This technique of stowage will ensure the absence of slipping and shifting of boxes in the package and will prevent them from overturning in extreme situations that may arise during the transportation of HG by road transport. The numerical values of the fractal dimensionality of the projections of the cargo frame model could be increased if the restrictions on the modularity parameters of the component elements of the package were removed.

Fractal scheme for stowing containers with HG, with elements of geometric blocking of it in the package, provides the most effective and low-cost technology for fastening the package in the container and is the safest during transportation. Such a scheme involves only the circular binding of the upper layer of the loaded package of boxes and its attachment to the car platform at four basic points.

Other test variants of stowage gave smaller values of the fractal dimensionality of the projections of the frames of the molded packages than the values shown in Fig. 13. However, they were always greater than the values of the fractal characteristics of the reference stowage (Fig. 9). These indicators provide information about incomplete blocking of package elements relative to one of the axes of the spatial coordinate system. And the grid coverage of the large-scale fragmentation of the frame of the packaged cargo in the program for calculating the fractal dimensionality «Java Applet to Compute Fractal dimensionalities» immediately gives information about the weak points of the blocking of the package model, which can be improved.

The limitation of the application of the proposed technique for the fractal stowing of cargo components is the requirement of modularity of the elements that enable the locking of the box container with HG.

The main drawback of the reported results is the lack of recommendations regarding the influence of specific numerical values of fractal dimensionality of the packed cargo on the quality indicators of the blocking of its elements in the spatial coordinate system.

Further research is planned to be associated with the construction of a grading system for the influence of values of the fractal dimensionality of the frames of the package elements on the quality indicators of blocking them from movement under dynamic loads during transportation. This will make it possible, in our opinion, to reduce the cost of using various techniques for effective fastening of the container during its transportation by road transport.

7. Conclusions

1. A general principle of calculating the fractal dimensionality of three-dimensional voxel-represented objects has been devised. The calculation is based on the procedure of cutting the model of an object into separate layers, reducing the dimensionality of the space for each layer, and determining the fractal dimensionality of the model through the fractal dimensionality of individual two-dimensional slices. The proposed principle could be applied to estimate the fractal dimensionality of three-dimensional objects in practical tasks of any fields where such models are used.

2. A technique for the simplified calculation of fractal characteristics of three-dimensional bill of lading models of cargo stowage using the software tools «FrakOut» and «Java Applet to Compute Fractal dimensionalities» was developed. The technique is based on the principle of reducing the dimensionality of the space for calculation. The assessment of the quality of the blocking of individual elements of the spatial system in three coordinate directions was determined by the indicators of the fractal dimensionality of the projections of the framework of the set of its constituent elements onto three coordinate planes. The technique has opened up possibilities for calculating the quantitative characteristics of the quality of cargo stowage from the point of view of its transportation safety.

3. A technique for the fractal stowing of HG in a box container on a car platform has been proposed. The fractal scheme of cargo stowage made it possible to control the characteristics of the blocking of package elements relative to one, two, or three axes of the spatial coordinate system. The basis of the construction of cargo stowage schemes is the introduction of additional lines into the frameworks of the constituent elements on the two-dimensional images of the package. This led to an increase in the numerical values of the fractal dimensionality of the projections of the frameworks of the constituent elements in comparison with the standard stowage, which means that it increased the degree of their geometric blocking. This technique of fractal stowing enables the absence of sliding and shifting of boxes in the package and makes it impossible for them to overturn in extreme situations, thereby improving the safety indicators of transportation of HG. At the same time, the use of the fractal technique of stowing will allow applying the most effective and low-cost technology of fastening HG as it involves only the circular binding of the upper layer of the loaded package of boxes and its fastening to the car platform at four basic points.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Popov, O., Iatsyshyn, A., Pecheny, V., Kovach, V., Kovalenko, V. (2023). Approaches to Assessing Consequences of Accidents During Transportation of Hazardous Substances by Road. Studies in Systems, Decision and Control, 327–342. https://doi.org/10.1007/978-3-031-22500-0_22
2. Guo, J., Luo, C. (2022). Risk assessment of hazardous materials transportation: A review of research progress in the last thirty years. Journal of Traffic and Transportation Engineering (English Edition), 9 (4), 571–590. https://doi.org/10.1016/j.jtte.2022.01.004
3. Bęczkowska, S. (2019). The method of optimal route selection in road transport of dangerous goods. Transportation Research Procedia, 40, 1252–1259. https://doi.org/10.1016/j.trpro.2019.07.174
4. Menoni, S. (2007). Transportation Of Dangerous Goods. NATO Science for Peace and Security Series C: Environmental Security, 97–110. https://doi.org/10.1007/978-1-4020-6385-5_6
5. ADR 2023 - Agreement concerning the International Carriage of Dangerous Goods by Road. Available at: https://unece.org/transport/standards/transport/dangerous-goods/adr-2023-agreement-concerning-international-carriage
6. Kurpel, D. V., Scarpin, C. T., Pécora Junior, J. E., Schenekemberg, C. M., Coelho, L. C. (2020). The exact solutions of several types of container loading problems. European Journal of Operational Research, 284 (1), 87–107. https://doi.org/10.1016/j.ejor.2019.12.012
7. Bortfeldt, A., Wäscher, G. (2013). Constraints in container loading – A state-of-the-art review. European Journal of Operational Research, 229 (1), 1–20. https://doi.org/10.1016/j.ejor.2012.12.006
8. Conca, A., Ridella, C., Sapori, E. (2016). A Risk Assessment for Road Transportation of Dangerous Goods: A Routing Solution. Transportation Research Procedia, 14, 2890–2899. https://doi.org/10.1016/j.trpro.2016.05.407
9. Junqueira, L., Morabito, R., Sato Yamashita, D. (2012). Three-dimensional container loading models with cargo stability and load bearing constraints. Computers & Operations Research, 39 (1), 74–85. https://doi.org/10.1016/j.cor.2010.07.017
10. Lim, A., Ma, H., Qiu, C., Zhu, W. (2013). The single container loading problem with axle weight constraints. International Journal of Production Economics, 144 (1), 358–369. https://doi.org/10.1016/j.ijpe.2013.03.001
11. European Commission, Directorate-General for Mobility and Transport, (2014). Cargo securing for road transport : 2014 European best practices guidelines, Publications Office. https://doi.org/10.2832/80373
12. Pankratov, A., Romanova, T., Litvinchev, I. (2020). Packing Oblique 3D Objects. Mathematics, 8 (7), 1130. https://doi.org/10.3390/math8071130
13. Chekanin, V. (2020). Solving the Problem of Packing Objects of Complex Geometric Shape into a Container of Arbitrary Dimension. Proceedings of the 30th International Conference on Computer Graphics and Machine Vision (GraphiCon 2020). Part 2, paper50-1-paper50-13. https://doi.org/10.51130/graphicon-2020-2-3-50
14. Pustiulha, S., Samostian, V., Tolstushko, N., Korobka, S., Babych, M. (2017). Fractal diagnostics of the degree of fuel atomization by diesel engine injectors. Eastern-European Journal of Enterprise Technologies, 6 (8 (90)), 40–46. https://doi.org/10.15587/1729-4061.2017.116104
15. Pustiulha, S., Holovachuk, I., Samchuk, V., Samostian, V., Prydiuk, V. (2019). Improvement of the Technology of Tribostate Application of Powder Paints Using Fractal Analysis of Spray Quality. Advances in Design, Simulation and Manufacturing II, 280–289. https://doi.org/10.1007/978-3-030-22365-6_28
16. Pustiulha, S., Samchuk, V., Samostian, V., Prydiuk, V., Dembitskij, V. (2022). Influence of the City Transport Route Network Discrete Model Geometrical Parameters on a Quality of a Passenger Traffic System Operation. Lecture Notes in Networks and Systems, 740–751. https://doi.org/10.1007/978-3-031-20141-7_66
17. Feder, J. (1988). Fractals. Springer US. Springer. https://doi.org/10.1007/978-1-4899-2124-6
18. Mandelbrot, B. B. (1983). The fractal geometry of nature. Henry Holt and Company, 468.
19. Pustiulha, S., Samchuk, V., Holovachuk, I., Lelyk, I., Klak, Y. (2022). Discrete-voxel representation of object models for the identification and calculation of their fractal parameters. Applied Geometry and Engineering Graphics, 103, 185–200. Available at: http://ageg.knuba.edu.ua/article/view/273596
20. Zlatanova, S., Ren, F., Xu, Y., Laefer, D. (2024). Editorial: Voxel-based modelling of natural and man-made objects. International Journal of Applied Earth Observation and Geoinformation, 128, 103713. https://doi.org/10.1016/j.jag.2024.103713