MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
VOLODYMYR DAHL EAST UKRAINIAN NATIONAL UNIVERSITY

Mykola I. Gorbunov
Oleksii V. Fomin
Viacheslav V. Kovalenko
Rostyslav Yu. Domin

THEORETICAL FOUNDATIONS FOR CONCEPTUALLY NEW ROLLING STOCK MODULES

(Part 1)

Sievierodonetsk
2017

UDC 629.4.02.001.76 + 629.4.027:625.1.03
BBK 39.24
F762

This monograph is recommended for printing by the Science Council of Volodymyr Dahl East Ukrainian National University (protocol No 12 dd 27.06.2017)

Reviewers: ***V.L Horobets,*** doctor of Technical Sciences, principal researcher of scientific and research testing centre on dynamics and strength of the rolling stock of Dnipropetrovsk National University of Railway Transport named after academician V. Lazaryan
V.H Masliiev, doctor of Technical Sciences, professor at Electronic system and complex of vehicle, National Technical University "Kharkiv Polytechnic Institute"
O.V. Ustenko, doctor of Technical Sciences, professor, dean of Faculty of mechanics and Energy, professor at Chair of Operation and Maintenance of Rolling Stock at Ukrainian State University of Railway Transport (UkrSURT)

Reference

F762 Gorbunov M. I, Fomin O. V, Kovalenko V. V, Domin R. Yu. (2017) Theoretical foundations for conceptually new rolling stock modules. Part 1. Sievierodonetsk: Volodymyr Dahl East Ukrainian National University. 100 p.

ISBN

The existing procedure for rolling stock synthesis applies the conventional methods of design and material selection. Having the objective to change the technical-and-economic indexes for the rolling stock with regard to the contemporary science and technology development, we need breaking through technologies, scientific concepts and new engineering solutions capable to increase the system efficiency. This monograph reports on the results of the research carried out by the team of the scientists for defining the ways of theorizing the design of conceptually new modules of the rolling stock.

We wrote this book for scientists and engineers whose fields of the professional expertise are related to design and research of railway rolling stock, it also could be useful for the university teachers, students, post-graduate students of the named sphere.

УДК 62-83: 669.02/09: 621.771
ББК 31.291
Ф17

ISBN

Abstract

According to the estimations of the Ukrainian and foreign specialists working in the field of transport, the following years are expected to show the increased volumes of railway transportations. This creates the necessity to develop the rolling stock, which is to ensure the maximal effective work of the railway station at observing all the conditions of the traffic safety. Therefore, the development and operation of the efficient rolling stock able to perform at maximum possible parameters of the efficiency, are to build the ground of the economic well-being of the world's railway transport. Especially acute the indicated issue is for Ukraine, a machine-building country with rather vast cargo turnover and substantial transit potential. However, it is infeasible to reach the maximum possible parameters of the rolling stock effective performance only by applying conventional approaches of synthesis without principally new designs if the target is also to ensure the faster movement and heavier loads on the axes along with the own minimal weight but without the decrease in the service life.

This monograph aims at development the theoretical foundations for synthesis of the conceptually new modules of the rolling stock to allow the development of the similar transportation means with significantly higher parameters of efficiency than those of the world's leading alternatives.

We devote this book for scientists and engineers whose field of the professional expertise is related to design and research of railway rolling stock, it also could be useful as a text book for the university teachers, students, post-graduate students of the named sphere.

Key words: transport, rolling stock of railway stations, transport mechanics, systematic approach, designer's idea, idealization.

CONTENTS

INRODUCTION

According to expert opinion, the experience of operating the rolling stock in European countries and in Ukraine indicates the absence of breakthrough science-intensive designs and technologies. Obviously, this situation is the reason why the rail transport loses in favour of the automobiles. The contemporary unit of rolling stock pocessing the conventional design is insufficient for the use in a prospective rolling stock with increased speeds and loads on the axles.

The engineering survey of the developed rolling stock projects aims at solving an important actual scientific and applied problem [1, 7, 9] of developing rolling stock models of international standard modular type. They are characterized by the substantially better boundary parameters for the contemporary science and technology (service life cost, cargo transportation efficiency, speeds under loaded and empty conditions, time of non-maintenance operation, repairability, carrying capacity, body load capacity, dynamic qualities, material use efficiency, safety indicators, etc.) than the best world analogues. This will enable Ukrainian railroad vehicles manufacturers to take leading positions on the world market among freight wagon manufacturers and importers, as well as to increase the cost-effectiveness of domestic and transit cargo transportation.

With our monograph we target the main purpose to create the theoretic fundamentals of synthesis for conceptually new modules of rolling stock, which is to allow us generating the vehicles with much better performance indicators than the best world's analogues.

1. DEVELOPMENT OF THE STRUCTURAL AND FUNCTIONAL SCHEME OF SYSTEMATIC APPROACH WHEN ROLLING STOCK DESIGN: A CASE STUDY ON THE LOCOMOTIVE UNDERCARRIAGE

1.1. Development of the Structural and Functional Scheme of Systematic Approach for Locomotive Undercarriage Design

The main difficulty in creating highly efficient models for the railway rolling stock [11, 21] is its interdisciplinary nature owing to the fact that the scientific issues, that constitute the essence of the problem, belong to the competence of different scientific directions, different methodological principles and different leading theories.

Regarding this problem solution in the sphere of railway locomotives, we utilize the existing experience of locomotive constructions, which convinces that the way out is possible on the basis of contemporary scientific principles of systematic approach [3, 4, 9, 11, 20. 21] applied for the development of complex tests, continuous introduction of new techniques to ensure maximum effect and to minimize the costs in the selection, justification and acceptance of design and technological solutions.

Moreover, in the studies on the development of highly efficient railroad transportation systems and its undercarriage, the orientation tends to be toward solving a particular problem. This is a fully justified and natural process of movement along the path from the particular to the general. However, in such complex cases, the sum of particular solutions is not always effective for the system in general. Therefore, the role of a holistic view to the problem solution is significant as it gives the systematic approach to a scientific and methodological basis bearing an organizational, theoretical, research, creative and logical origin.

Furthermore, from the standpoint of the applied aspect of the systematic approach [10. 11, 18, 21, 24], it is necessary to find solutions to those specific problems that arise during the system development and functioning. Therefore, the researchers and developers work by the following order:

- the general patterns of the research are to be determined, aiming at finding the best solutions to various problems;
- the targets are to be formulated, their ranking is to be performed;
- the systems are to be disaggregated into their component elements;
- the interconnections, existing both between the elements of the system as well as between the system and the environment and others, are to be determined.
- the development of integration principles for the various research methods and techniques (mathematical and heuristic) are to take place, the latter have been developed both within the framework of system analysis and in the framework of other scientific directions and disciplines but form a coherent, interdependent set of methods of system analysis.

The work completion should be in the form of the recommendations for the development of the fundamentally new systems or the improved ones.

Eventually, the problem solution for railway industry based on the systematic approach includes the following stages:

- determination and assessment of the main research areas;
- preparation and decision-making on the problem of developing the undercarriage with better functional qualities;
- development of theoretical and practical methods for conducting research with the objective to find the best solution by using mathematical simulation, decomposition analysis and control;
- analysis, compilation and evaluation of the results,
- implementation of the decision with scientifically grounded, pilot and experimental confirmation of the results at the each stage.

Graphically, the described approach can be expressed in the form of the general structural and functional scheme (refer to Fig. 1.1).

Thus, the main stages of the research are as follows: identification of the research areas, selection and use of the research methods, experimental confirmation of the results of these studies. The stages respectively have the certain order of implementation and let us regard it for the locomotive undercarriage.

The analysis and justification of the chosen research area, formulation of the targets and objectives are carried out within the first stage. The distinctive feature of this stage is the development of a comprehensive method of intellectual support

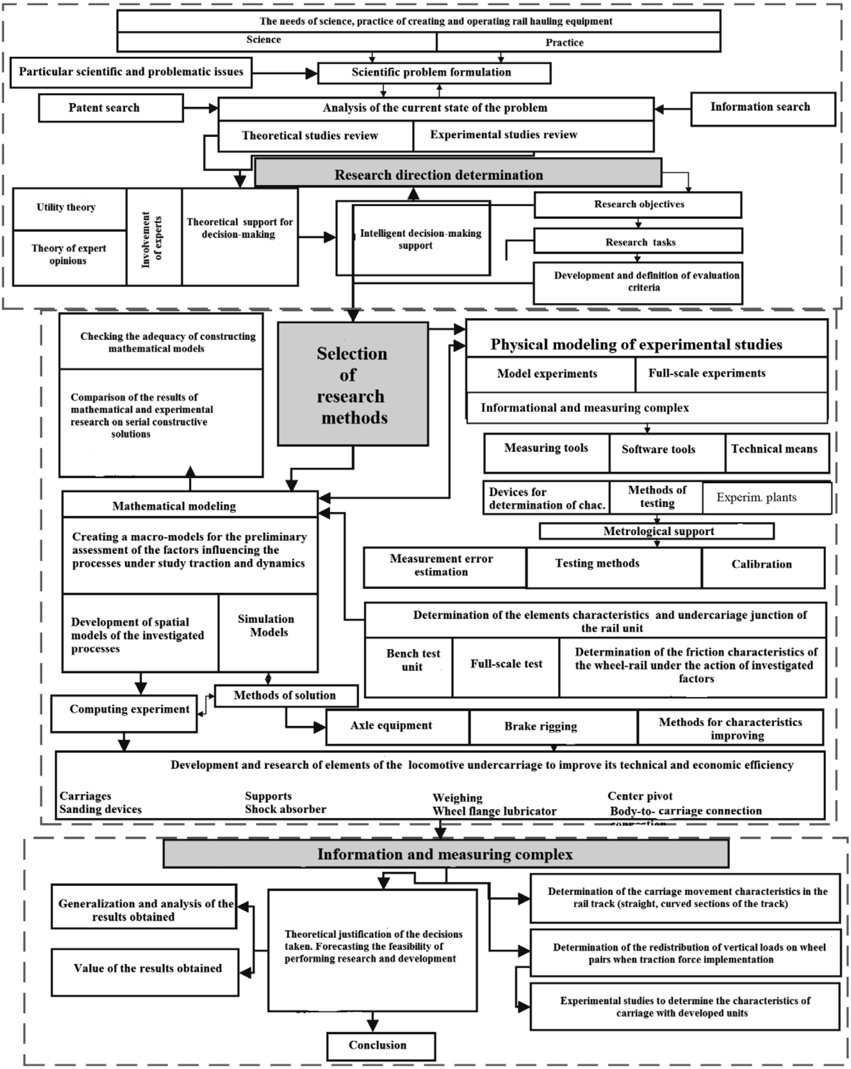


Fig. 1.1. Structural and Functional Scheme of Systematic Approach for the Study of Locomotive Undercarriage

for decision-making both at choosing the direction of the research and at creating new locomotive designs.

At the second stage, theoretical studies are to be carried out on the basis of mathematical simulation using the developed test equipment as a tool for monitoring the real characteristics of the units.

The third stage is based on the theoretical studies. A number of technical solutions have been proposed to improve the qualitative characteristics of the locomotive undercarriage, they have been verified with the help of the developed informational and measuring computer complex (IMCC) including test methods, testing equipment, test devices and automated processing of experimental results.

1.2. Rail Vehicle Complex Assessment

The assessment of the engineering system of such type as rail vehicle [2, 5-7] is a rather challenging task. For the solution of it, one needs not only to choose and to assess the main characteristics of rail vehicle such as, for example, speed, capacity, strength, dynamic indicators, haulage capacity and so forth, but to unite them in the one umbrella indicator. Provided that a complex indicator can be found, we can objectively assert that one rail vehicle design has the advantages over the other one; it means it possesses more optimal attributes. In principle, there are three possible assessment schemes of the object. They are carried out per the questions given in Table 1.1. The assessment itself is conducted by two ways:

a) tentatively;

b) objectively, that is grounded on certain criteria.

Table 1.1

Schemes to Assess the Objects

Scheme	Object to assess	Assessing question type
I	Implemented engineering system	What kind of the engineering system is this?
II	Statement of the problem (the list of requirements) and solution variants or the sample	Does the system or (model) correspond to this statement?
III	Statement of the problem and various possible solutions, which correspond to the problem statement from the standpoint of feasibility	Which of the solutions is better (optimal)?

Tentative assessment, in spite of its subjectivity, should not be neglected. It is conducted not only by the subjective feelings and ideas, but often stipulated by many years of experience and expertise. That is the reason why the skills of the tentative assessment should be regularly developed to allow placing confidence in so called designer’s intuition. This is especially important at the beginning of the design development when there is no much information of the object to be developed.

The problems of transformation for the assessments into the umbrella indicator are as follows.

a) In order to have the objective assessment, there should be the determining criteria chosen. Moreover, this is normally grounded on the fact that the engineering system possesses the set of values and each of them is defined by the needs it meets and their extent. In case of the railway rolling stock, the notion of technical merit matches the set of technical characteristics of a given system such as performance, maintenance and production. Here, the characteristics of fabricability and constructive features can be incorporated. They are absolute indicators. Apart from them, a number of relative indicators can be singled out. For this, we need to determine a perfectly fabricated article as the bearer of the perfect properties. Thus, the relation between the actual value and that of the perfectly fabricated article is the relative indicator of the value.

b) The important step in the assessment is the choice of the determining characteristics in the criteria system. That means that the common rule for this kind of choice is the capability to provide rather complete overview of the system. The common rule, however, makes us to use reasonable limitations in many cases as the great number of the properties selected for the assessment leads to narrowing the overview. The choice of the characteristics is to be done with respect to the possibility of the quantitative assessment. Furthermore, this choice is influenced by the assessment target as well as by the stage of the engineering system development. As an example can serve the engineering system, which at the stage of the sketch project can be evaluated in a different way than at the stage of the developmental prototype.

Some degree of freedom for the criteria is in the first and the third assessment types, while the second type is determined by the requirements to have been formulated earlier (refer to table 1.1).

c) Although many of the characteristics or criteria could be assessed quantitatively, nevertheless there arise the difficulties related to their integrating into the umbrella indicator, because the different characteristics are expressed in different units. Here, it is better to apply the grades. In this case, the embodied part of the criterion can be evaluated by the certain number of grades. For example, rating from 4 (excellent) to 0 (unsatisfactory) at 5-grade system.

Such an approach allows us to assess different properties uniformly, that is very important for a generalized estimator. It should be highlighted that the grade of unsatisfactory is not acceptable for the crucial properties. On the other hand, the complete realization of less important properties is not obligatory.

d) Prior to the mathematical treatment, we should decide if it is sufficient for the generalized estimator with certain grades to have the arithmetic mean or the weighted average preferable as the latter takes into consideration the importance of some properties. In the both cases, the one-dimensional comparison is regarded.

Multidimensional expression is available only with application of geometric means. In this case, the generalized estimator can be written as the area of a polygon or the volume of a space polygon and their linear parameters are the estimates of certain properties.

The generalized estimator can be defined as vector sum (radius vector, the components of which are the estimates of the properties).

The various techniques to acquire assessments are given in table 1.2.

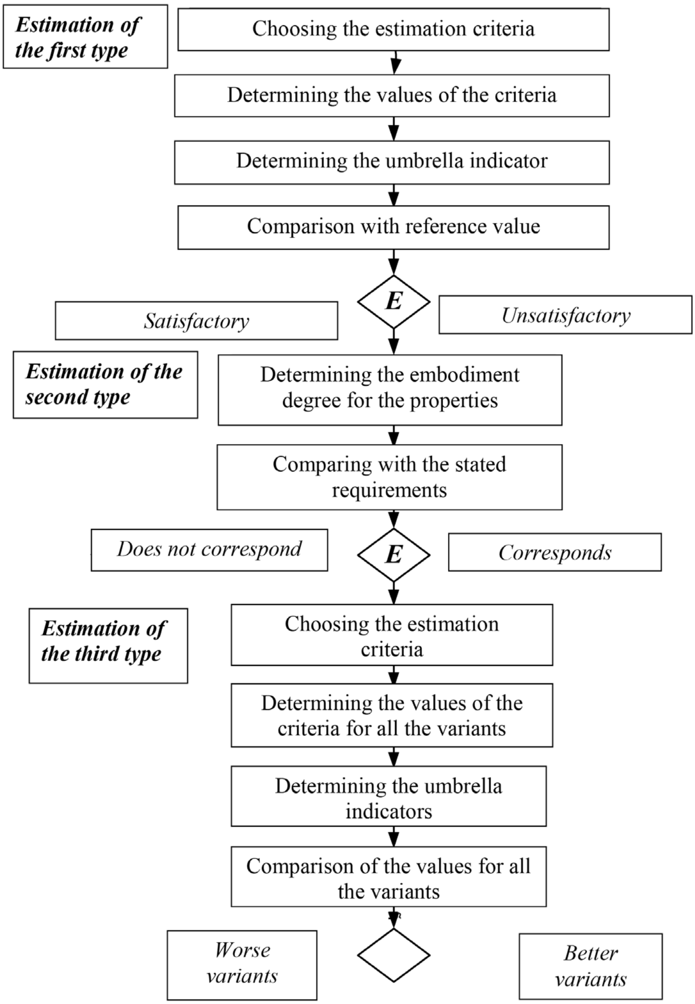


Fig. 1.3. Estimation Schemes for Technical Facilities

Table 1.2

The Techniques to Process the Grade Estimation in Order to Determine the Value of the System

Type of the generalized estimator	Formula	Geometry	Remarks
1	2	3	4
1. Absolute arithmetic mean	$\overline{p}_1 = \frac{\sum p_i}{n}$		Simple calculation
2. Relative arithmetic mean	$\overline{p}_2 = \frac{\sum^n p_i}{np_{\max}} = \frac{\overline{p}_i}{p_{\max}}$	Average value	Compare with the perfect version $p_2 \le 1$
3. Weighed absolute arithmetic average	$\overline{p}_3 = \frac{\sum p_i g_i}{\sum g_i}$		Take into account the importance of the properties
4. Weighed relative arithmetic average	$\overline{p}_4 = \frac{\sum p_i g_i}{\sum p_{\max} g_i} = \frac{\overline{p}_3}{p_{\max}}$		$\overline{p}_4 \le 1$
5. Absolute geometrical average	$\overline{p}_5 = \sqrt[n]{p_1 ... p_i ... p_n}$	Side of n-dimensional cube equivalent to the plate with sides $p_1 ... p_n$	$p_5 = 0$ at $p_i = 0$
6. Relative geometrical average	$\overline{p}_6 = \overline{p}_5 / p_{\max}$		$\overline{p}_6 \le 1$
7. Weighted absolute geometric mean	$\overline{p}_7 = \frac{\sqrt[n]{p_1 g_1 ... p_n g_n}}{\sqrt[n]{g_1 ... g_i ... g_n}}$		Insignificant since g is like para. 4
8. Weighted relative geometric mean	$\overline{p}_8 = p_7 / p_{\max}$		
9. Absolute vector	$\overline{p}_9 = \sqrt{p_1^2 + p_2^2 + ... p_n^2}$		
10. Revative vector	$\overline{p}_{10} = \overline{p}_9 / p_{\max}$		$\overline{p}_{10} \le 1$
11. Weighted absolute vector	$\overline{p}_{11} = \sqrt{(p_1 g_1)^2 + ... + (p_n g_n)^2}$	Diagonal line n-gauge block with sides of $p_1 ... p_n$	
12. Weighted revative vector	$\overline{p}_{12} = \overline{p}_{11} / p_{\max}$		$\overline{p}_{12} \le 1$

Notes:

p_1 - p_n - criteria estimation in grade system;

1, … n - index of grade estimations of the perfect version;

g_1 - g_n - value of the estimation criterion;

$\overline{p}$ - generalized estimator;

n - number of estimation criteria;

$\sum_{i=1}^{n} \overline{p}_i = \sum_{i=1}^{n} p_1$ - the sum of estimation grades from to .

The most challenging is to determine the factors to have the opportunities for rail vehicle estimation. If we take into account that the primary function of transportation is to provide heavier carrying capacity of freight and high-class comfort of passenger transportations, then it is better to conduct estimation by driving and dynamic qualities. The most crucial factors to estimate these indicators are shown in table 1.3.

Table 1.3

Factors to Estimate the Rail Vehicles Efficiency

Driving and dynamic qualities
1. Vertical dynamic coefficient: 1.1. The first stage of spring suspension; 1.2. The second stage of spring suspension;
3. Horizontal dynamic coefficient
4. Vertical dynamic forces
5. Maximal lateral forces
6. Traction force
7. Average is embodied at the area of the driving force

In table 1.3, dynamic properties of rail vehicles are taken into account by points 1-4 horizontally and vertically, while points 5 and 6 deal with driving characteristics of the rail vehicles. The estimation criteria are discussed in chapter 1.1.

2. IDEAL OPEN WAGON CONCEPT

2.1. General Provisions of the Proposed Ideal Open Wagon Concept

A characteristic feature of those design works, which target improving on the technical and economic operation parameters (TEOP) in the field of freight cars, is the use of engineering software complexes only at the stages when checking the strength properties of open wagon bodies under development. The current level of computer technology (that is, the volumes of operational and accumulative memory, the speed of the calculating devices, achievements with the artificial intelligence) can significantly expand the capabilities of the designer when generating and new baselines of open wagons and their complete set of constituents.

The things mentioned above justify the need to develop a conceptually new theoretical basis for the design of open wagon bodies, which will use advanced methods and approaches to optimized automated design of vehicles, modern computer facilities, accumulated experience in the manufacture and operation of open wagons. It is assumed that the practical implementation of such a development will greatly modernize already existing models of open wagons and generate new ones.

For the development the mentioned theory at the first stage, it is planned to create a set of requirements for open wagon body designs, implementation of which is to ensure the achievement of the maximum possible values of their TEOP under given conditions of production and operation. However, the results of the analysis of scientific and professional technical literature on the profile of the issue under consideration have revealed the absence of the specified information.

The perfect [8, 21, 23, 25] open wagon body is the body which is able to carry the maximum cargo with the minimum production and operating costs under specified conditions of the production base and the territorial navigation. It is proposed to present the perfect body of the open wagon in the form of a virtual lining, which is characterized by the indicators and parameters that satisfy the above-mentioned requirements. Moreover, one of the key roles in the formation of the prime cost for open wagon body manufacture is the adaptation of its design to the resource and technological base planned for the construction, it includes the following issues which are to be taken into consideration: the cost of energy and working resources, focus on the foundry or assembly-welding technologies, existing equipment, etc.). This is evidently a complex scientific and engineering task, that requires detailed and separate consideration, therefore in this paper the definition of operational requirements for a perfect open wagon body is being observed.

2.2. Defining Ideal Open Wagons Indices and Parameterization

The procedure of defining the corresponding indices and parameters is given in Figure 2.1 in the form of an algorithm.

At the first stage of the algorithm it is suggested to create the source data base with the definition of the following characteristics: the territorial navigation of the wagon; cargo planned for transportation; equipment of the wagon. The territorial characteristics include the size of the rolling stock; permissible radii of the curves and sorting slides; temperature, wind and decay characteristics of the territory of operation; permissible axial load ($P_{ax.}$).

Let us consider some of the constituents. The cargo can be described by the following:

- geometrical properties;
- need for fixation during transportation;
- density (ρ);
- specific features of loading and discharging (loading and discharging temperature, the necessity to apply the additional equipment, the necessity of discharging in inter-city / foreign-space or on carriage discharger).

The equipment of the wagon (the module of the undercarriage, auto-coupling equipment and braking equipment) is characterized by

- geometric parameters (overall dimensions, contour and shape features);
- masses;
- installation and mounting features;
- time for maintenance and repairs;

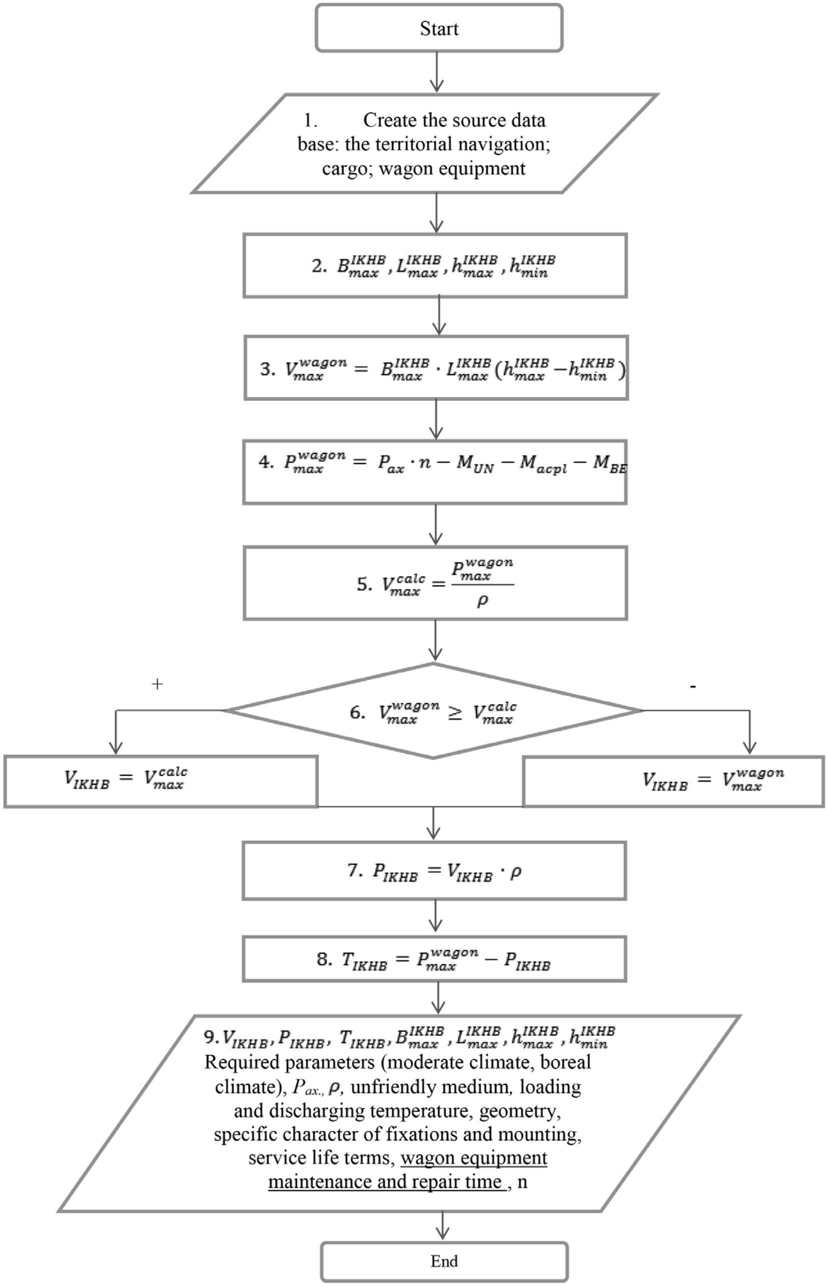


Figure 2.1. Algorithm to Define Indices and Parameters of Perfect Open Wagon Body

- structural features (for example: it is buckling *(n)* for the undercarriage, for braking equipment - separate braking system or system with one brake cylinder, for auto-coupling equipment - power consumption of damping devices, etc.).

Taking into account the current source database, the following indicators of the perfect open wagon body are determined, based on the sizes of the chosen dimensions as follows:

- the maximum width B_{max}^{IKHB} and height h_{max}^{IKHB};
- the maximum length value L_{max}^{IKHB} is determined as dependent on the minimum allowable radius of the curves and the requirements for the coupling equipment of the wagon;
- the minimum body height h_{min}^{IKHB}, depending on the structural features of the equipment of the undercarriage modules (height of center plate arrangement) and the auto-coupling equipment (the height from the level of the rail head to the axle of the coupling and the highest point, taking into account the installation of the yoke).

At the next stage, the loading volume of the body $\left(V_{max}^{wagon}\right)$, maximally possible under given conditions, is defined as the multiplication of B_{max}^{IKHB} by L_{max}^{IKHB} and the difference between h_{max}^{IKHB} and h_{min}^{IKHB}.

After that, we define the maximum possible load carrying capacity $\left(P_{max}^{vagon}\right)$, as the difference between maximum gross mass of wagon (counted by multiplication of P_{ax} by n) and the total mass of the undercarriage modules (M_{UN}), auto-coupling equipment (M_{acpl}) and brakes equipment (M_{BE}).

At the fifth stage, based on the cargo planned for transportation, we determine the calculated loading volume of the body $\left(V_{max}^{calc}\right)$, as a ratio P_{ax} and ρ. After that, the loading volume for the ideal open wagon body is developed as V_{IKHB}, that equals V_{max}^{calc}, if $V_{max}^{wagon} \geq V_{max}^{calc}$, or V_{max}^{wagon} if not.

Taking into account the obtained value of V_{IKHB}, we define the ideal open wagon body load carrying capacity (P_{IKHB}) as multiplication of V_{IKHB} and cargo density (ρ).

The tare or the own weight of the ideal open wagon body is defined as the difference between the maximum possible load carrying capacity $\left(P_{max}^{wagon}\right)$ and P_{IKHB}. After that, we create the database of the indices obtained and parameters of the ideal open wagon body for the further stages of designing, which includes: V_{IKHB}, P_{IKHB}, T_{IKHB}, B_{max}^{IKHB}, L_{max}^{IKHB}, h_{max}^{IKHB}, h_{min}^{IKHB} as mandatory (e.g. moderate climate, boreal climate); $P_{ax.}$, ρ, cargo aggressivity, characteristic properties of loading and discharging, geometrical parameters, fixing and installation properties, terms of service and terms of wagon equipment repair (the minimum desired service life of the ideal open wagon body equals the service life of the undercarriage module), *n*.

As an example of the proposed algorithm application, the information below can serve, it determines the indicators and the parameters of the perfect open wagon body, which is planned to be used for coal transportation within the territory of the CIS countries.

In this case, the territorial characteristics are as follows:

- 1-BM size or clearance limit in accordance with GOST 9238; the radius of the curve (the region of the conjugation of the straight line and the curve but without a transition radius to provide automatic coupling) – 135 m, S-like curve radius – 120 m, circular radius – 60 m;
- the body design for boreal climate is regarded as a product of I category according to GOST 15150; $P_{ax.}=23.5$ *t/axis*.

The load characteristic properties include:

- the absence of fixation requirement for the period of transportation;
- $\rho=0.85$ *t/m*^{3};
- the loading temperature and outside temperature are equal;
- use of dumping machine for discharging or tippler pumping is possible.

The characteristics of the wagon equipment are the following:

- the module of the undercarriage for cars of 18-100 (type 2 according to GOST 9246);
- $M_{UN}=9.8$ *t*, $n=4$;
- mandatory wagon base – *8.65 m*;
- the term of service is 32 years,
- the distance from the level of the rail head to the center plate arrangement is 806 mm;
- the distance from the level of the rail head to the axle of the autocoupling is *1060 mm*; that to the top of autocoupling module - *1228 mm*, $M_{acpl}=1.16$ *t*;
- the damping devices belonging to the class not lower than T1 according to SOU MPP 45.060-327:2010;
- the length of the console from the plate arrangement center to the center of the autocoupling shaft hinge – *1.765 m*;
- separate brake system, $M_{BE}=0.52$ *t.*

Taking into account the given database, the parameters and characteristic properties of the ideal open wagon body are as follows: $B_{max}^{IKHB}=3.4$ *m;* $h_{max}^{IKHB}=3.85$ *m;* $L_{max}^{IKHB}=13$ *m;* $h_{min}^{IKHB}=1.238$ *m*; $V_{IKHB}=97.08$ *m*^{3}*;* $P_{IKHB}=82.52$ *t;* $T_{IKHB}=0$ *t.* Moreover, the mentioned indicators and parameters can be used as the target values of the design or the upper limit of possible solutions while as the indicators of the lower boundary can be used those acceptable indicators at which the competitiveness of the body being designed is ensured. It is advisable to use the corresponding best designs of the analogues. Thus, currently, these indicators are as follows: $V_{analogue}=76...90$ *m*^{3}*;* $P_{IKHB}=70$ *t* $T_{IKHB}=11.7$ *t.*

Based on the obtained indicators and parameters, it is possible to formulate target functions for design optimization.

The determined indices and parameters of the ideal open wagon body become basic for the further stages of the development.

2.3. Identifying the Perfection Degree for Freight Wagons

For the sake of the scientific and technical solutions directed towards the development of freight wagons with high TEOP it is necessary to generate the new structural and functional schemes. This substantiates the necessity, timeliness and relevance of the conceptually new theoretical basis for this type of design. Such a theory should be based on the perspective views including the ideology of engineering means creation, advanced methods and aspects of adaptive optimization for automated design, modern computer facilities, accumulated experience gained with freight wagon manufacture and operation. However, the results of the analysis carried out on the reference, specialized scientific and technical literature related to the profile of the issue under the study has pointed to the absence of the relevant content development in them, which, in its turn, inhibits the evolution of domestic freight wagon structures.

This chapter highlights those publications that aim at approaching the ideality degree for freight wagons [8, 21, 23, 25] and forecasts the next generations of their carrying systems. This work also provides the formula to evaluate the ideality degree for freight wagons and its application is illustrated with the example of carrying systems for open wagons. Here are the instances how the reported general approaches of idealization are used for carrying systems of open wagons.

The international experience shows that the progress of the engineering system can be described by the regularity in its perfection increase that means that the engineering system is approaching the ideality conditions. Moreover, the theories have been developed to detect how this regularity acts and define the perfect object design and the ways of gradual striving to it; their actual implementation evidences the perspective of this direction and gives the positive experience. However, the results of the study on the problem of scientific publications, technical literature, and reference literature availability witnesses the absence of the reference sources where methodological fundamentals in the ideality aspect are formulated with the objective to focus on the development of freight wagon designs. Thus, being based on the idea that the idealized approach is able to bring us closer to achieving perfection in freight wagon design, the authors propose the new direction of engineering for freight wagons by utilizing ideality-oriented strategy. The chosen direction for new generation of freight wagons has justified the necessity to develop the appropriate scientific and theoretical base. In order to target the mentioned, the following common statements have been assumed: idealization is regarded as the process of building the notions of the object *mentally* or *virtually* while this object does not exist in the reality but there is its prototype in the real world. The well-known similar examples are the notions of point, perfectly rigid body and ideal gas. Thus, the perfectly ideal system is the system which does not exist in the reality but all its functions are performed at the certain instant and in the certain location within this system and 100 % calculated load is being born by the system itself without consuming any matter, energy or finance.

Within the frame of the new theoretical fundamentals for new generation freight wagon design, has been proposed the concept of their perfect construction, the peculiarities of which are described in the previous chapter as an example of the perfect body module for open wagons. According to the developed concept of the perfect open wagon body, we regard as perfect the construct of the body module or the carrying system otherwise it is the perfect mental or virtual object laying in the base of the material notion of the open wagon body model, defining its sense. At this, it is characterized by the indicators and parameters which provide maximum cargo transfer with minimal or even zero prime cost of fabrication and operational costs under certain production conditions and within certain territory. The boundary of idealization for open wagon carrying systems is its decrease and its final vanish at simultaneous increase in the number of functions to perform, that is, the perfect situation for this type of carrying systems is the absence of masses and own sizes but its functions are able to perform the service of placing the cargo at storing and transporting. Within the indicated procedure, the algorithm has been developed for determining the indicators and parameters of perfect carrying systems for open wagons. The actions done in accordance with the algorithm result in outlining the characteristics of the perfect open wagon body. However, the further development of the scientific base to be grounded on ideality-oriented strategy of design for new generation freight wagons requires the broader area of the appropriate knowledge gained by finding the solutions for the following tasks: 1) to determine the way for freight wagons to approach the ideal; 2) to develop the procedure for defining the perfection degree for the existing freight wagons or those under designer's development; 3) to produce the scientific forecast for freight wagon designs to be developed.

The analysis on the history of engineering system progress shows that all the systems, including those for freight wagons, are being developed by the sequences of events, which could be generalized as follows: 1) problem appearance; 2) formulating the main directed function (hereinafter refered as MDF) – the social order for the new engineering system; 3) the synthesis of the new engineering system, the start of its functioning (minimal MDF); 4) higher MDF as the attempt to obtain from the system more that it is able to give; 5) one of the parts or properties of the engineering system becomes insufficient sufferying from higher MDF as it gives the birth to the engeneering contradiction when the first opportunity to formulate the scientific and inventive task. For freight wagons this contradiction is expressed as the constant necessity to increase the cargo mass at lowering the costs of their operation; 6) formulating the necessary changes of the engineering system as the search of the answers for the questions of *What is necessary to do for higher MDF?* and *What prevents this to be done?* It means the transformation into the scientific and inventive tasks; 7) the solution of scientific and inventive tasks with the use of the knowledge from the scientific, engineering and cultural spheres in general; 8) the changes in the engineering system appropriate for the invention; 9) increase in MDF (see step 4).

Let us consider in more detail the steps named above. Figure 2.2 shows the principles how the engineering system is born.

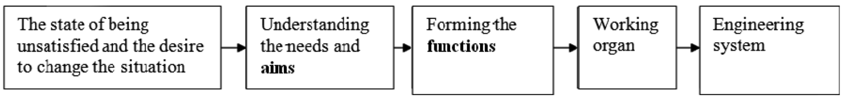


Figure 2.2. The Principle to Form the Engineering System

In figure 2.2, it is shown that the initial stages of the engineering system formation are obviously the processes which take place in the society, in particular, they are needs arising, target understanding and function formulating. In case of freight wagons, this can be described as understanding that there is a need in transportations of vast cargos (resources, energy carriers, building materials and machine-building products, etc.) for long distances accompanied by limited expenditures. However, the actually working function is the effect produced on the object under the work while for freight wagons this object is the cargo. This means that the necessity arise to create the working organ as the intermediate link between the function and the object, which bears MDF in pure form. For freight wagons, the working organ is the body module or the carrying system. Nevertheless, the working organ cannot carry out MDF independently at the initial stage that is why it is provided by the additional constituents. In case of freight wagons (hereinafter referred as FW), these constituents are the following: the module of undercarriage structure to provide the wagon run, the module of the brake system to provide wagon braking, and the module of connectors to provide coupling with the neighboring wagons or with the locomotive. Thus, by addition of the auxiliary modules (the module of undercarriage structure - MUS, the module of the brake system - MBS, the module of connectors - MC) to the working organ of the body module (BM) we obtain the engineering system (ES) of the fright wagon (FW)

$$FW(ES)=BM+MUS+MBS+MC. \tag{2.1}$$

In accordance with the common regularities for the engineering system development, when the engineering system appears, it begins to adopt the area of quality and the physical field by increasing in the own weight, size and power requirements including resource consumption, however, on reaching the certain limits, it starts to decrease or shrink. For the contemporary freight wagons the major limiting factors of the expansion are as follows: the sizes of the rolling stock, allowable axial load on the capping, design speed, factor of steel fatigue, competitive market price, etc. The right way of shrinking for the engineering system is considered to be its improvement, that is, approaching to the ideal. Apart from this, it should be noted that currently accepted perspective direction to improve the technical and economic operation parameters for freight wagons is to perform it by enlarging the allowable axial load on the capping. This stage means expanding for the engineering system called "rolling stock–railway track" and is the indirect evidence that the engineering system of freight wagon is developing.

Generally, it is recognized rational to show the engineering system expanding and shrinking as the changes in its indicator of the perfection degree.

In 1950s, at the first stage when the development of TRIZ, the theory of engineering solutions, Genrikh Altshuller introduced the notion of the *ideal system* as that which does not exist but its functions are being performed. This notion is highly useful for solving the certain invention tasks. However, at the end of 1970s, it became obvious that this theory does not allow one to obtain the desired results with the certain systems. At the same time B. Zlotin suggested that the notion of the engineering system perfection can be interpreted with the notion of the degree of perfection, as the ratio of the system efficiency and the sum of the factors paying for the system existence and its functions performance. In this case, the law by which the engineering system strives to achieve the perfection can be described by the changes of its degree of perfection with the following formula:

$$I = \frac{F_u}{\sum F_h} \to \infty, \tag{2.2}$$

where I – the degree of perfection for the engineering system;

F_u – efficiency of the engineering system (integrated indicator to show how the system performs the useful functions), that is, any complex of mutually agreed functions and properties for which the given engineering system exists. At this we mean the benefits which the engineering system gives to those who use it, create it or operate it. For the engineering systems of railway transport, F_u value is suggested to be generated on the base of its principle quality characteristics and the indicators of the work efficiency during its operation, which undergoes the control. In case of freight wagons, these indicators could be listed as the following: the tare (specific material consumption), carrying capacity, full or loaded volume of the wagon body, guaranteed time of service life, design speed, strength indicators and operation dependability, etc.

ΣF_h is the complex of factors paying for the useful functions, which include everything that the society invest in it including: 1) consumed resources; 2) expenses for the development of the given engineering system (idea birth, invention, design, manufacture, etc.) together with its operation, marketing transportation, recycling, etc.; 3) related to the system detrimental and adverse effects (pollution of the environment, damage from possible accidents, exhaustion of scarce resources, etc.); 4) the detrimental resources related to the system; they are not having any harmful effect at present but are able to bear them in the future. Speaking about the complex of the paying factors for the freight wagon useful functions it is suggested that the total price of the service life for freight wagons of the model under the study can be used. It reflects all the possible expenses of the participants in the idea birth and its existence. As the system of the detrimental and adverse effects caused by the manufacture and maintenance of freight wagons we can accept pollution of the environment and negative impact of the harmful by-products on the personnel (for example, heavy metals and gases) during the processes of metal structures manufacture (for instance: carriage casting, welding structures). Such influence may be expressed in the monetary equivalent spent at the corresponding filtering devices and compensations for the personnel.

The expediency of the further development for the operating engineering systems is justified by the degree of perfection expected to increase or to be sustained at the sufficient level. The determined condition defines the upper limit of expediency for the further development of the engineering system, when reaching its upper value there appear the justified preconditions to substitute the existing engineering system with the one of the new generation.

Now, consider the application of the proposed aspect for freight wagons using the case of four-axle open wagons as they are the most common and required types of wagons.

Figure 2.3 describes the general review how four-axle open wagons have been developing qualitatively and show the changes in the indicators: F_u, ΣF_h, and I depending on the time of their application on the railways of the CIS countries.

The figure also shows that the change of F_u for open wagons is described by S-like curve in which you can distinguish three periods of development.

The first period (P_1) is the initial period of 1906-1946. This period can be conventionally called as the launching of four-axle open wagon production with the first samples made in 1906 and further improvement during World War II. This period is characterized by an insignificant increase in F_u indicator along with the

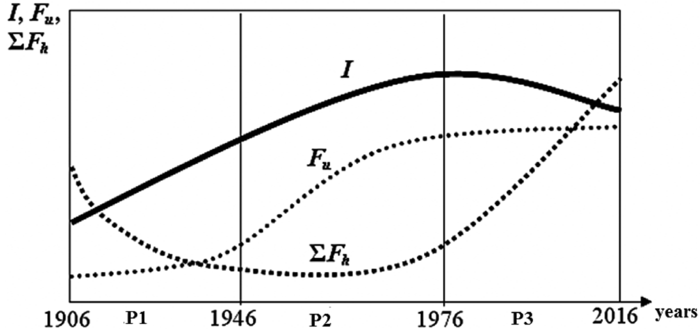


Figure 2.3. The Diagram of the Qualitative Development of Four-Axle Open Wagons

necessity to limit ΣF_h (due to the need to provide the performance, dependability and accident-free operation).

The second period (P_2) is the period of intensive development of four-axle open wagon (1946-1976). It is characterized by the steady increase in F_u indicator as a result of multifaceted work on the improvement of their structures, while limiting the growth of ΣF_h. It was during this period that the new system (the open wagon with corrugated steel lining, welding joints, blind walls, axle boxes with roller bearings, etc.) replaced the old one (the open wagon with wooden lining, rivets, sliding axle boxes, end doors, etc.), and became economically advantageous. In this case, the growth of its economic efficiency was guaranteed.

The third period (P_3) is the contemporary period (1976-2014) described by the steady stabilization of F_u indicator, keeping it closely to the level of the second period end, and constant growth of ΣF_h. The graph evidences that the past 40 years have not seen the drastic improvements in F_u indicator in the construction of open wagons. This is clearly witnessed by the fact that at the present time the principal indicators of the performance efficiency for open wagons (they are tare weight (m) in tons, carrying capacity (P) in tons, efficient loading volume of the body (V) in m^3) are conventionally at the level of the analogue wagons indicators ($m=22\text{-}24/5$ ton; $P<71$ ton; $V<9$ m^3) produced in 1980s (refer to models of 12-119 technical specification of *3-198-83*; 12-532 technical specification of *3-945-76*; 12-753 technical specification of *24.05.812-83;* 12-1505 technical specification of *24.00.806-82*). Thus, in spite of the designers' efforts, the development of open wagons does not keep up with the constantly growing needs of the participants in their life cycle. The engineering system of open wagons evolves, obtains the new external design but the drawbacks are still found. Moreover, the currently existing schemes and designs of open wagons have practically consumed their functional resource. Those improvements on the open wagons that are proposed today are anything but of little importance and do not permit the significant increase in F_u indicator while they are accompanied by inherent growth of ΣF_h constituents, in particular, the stress of the structural elements, dependability, cost of materials, which causes a reduction in their economic efficiency. This situation evidences that there is the necessity to develop and to implement the open-wagons of the new generation. Furthermore, the desired target could be achieved only by changes in the principle construction concept of open wagon design and modernization. Implemented within the contemporary structural and functional models of the open wagon principle construction, the design concept is based on the approximate calculations, utilized engineering experience (for example, the carriage structure of foreign production), materials and metal profiles of the previous century. Effective solutions that previously met the needs of the past are currently unacceptable.

In Figure 2.3, there is also shown the change in characteristic of the open wagon perfection degree (I), which proves its crucial role in assessing whether it is expedient to develop the considered engineering system further or to replace it. It is apparent that the development processes in the first and second periods are accompanied by an increase in the value of I: in the first case, mostly due to a decrease in ΣF_h while in the second case it occurs due to the advance of F_u growth. The further development in the third period is characterized by a decrease in the value of I owing to the growth of ΣF_h with practically unchanged F_u levels. This fact tells us that the further development for open wagons beyond the second period is not expedient and there is a need for the transition to the new open wagon generation, which is able to ensure the higher indices of their economic efficiency.

With the general review on the development of the freight wagons, we observe that regarded stages of open wagons development are also true to the freight wagons. That is the reason why the conclusions with open wagons may be also true to the other main types of contemporary freight wagons. Thus, it can be claimed that the problem of general increase in the perfection degree for freight wagons is topical today.

2.4. The Ways of Idealization for Freight Wagons

To define possible directions for increasing the degree of perfection for freight wagons we consider the possible ways of their idealization. It is known that the general ways for the engineering system to approach the ideal are: increasing the number of functions it fulfils; decrease in the working body; transition to the supersystem. It is also determined that when approaching the ideal, the engineering system initially opposes the forces of nature, then adapts to them, and eventually uses them for its own purposes. Below we describe in details the general ways of raising the degree of perfection for freight wagons that include as follows:

1) Reduction in some parts of freight wagons. It is expedient to do this by combining the functions of several elements into one or their rational redistribution. One of the promising methods of implementing this direction is the method of functionally perfect modeling. The essence of the method lies in the fact that the system is decomposed into elements and the functions of these elements are determined. The main functions and functions that contain unwanted effects are singled out. By the determined rules, the elements that contain features causing unwanted effects during their operation, are eliminated, except for the elements that bear the main functions. After that, it becomes clear, which functions after deletion remained undistributed between the remaining elements and the results allow us to obtain a functionally ideal model. This model defines the requirements, conducts their analysis, formulates the tasks and works with the previous proposals;

2) Elimination of some individual procedures, operations or processes. As an example, we can consider the procedure for lubrication of freight wagon axle boxes, which were initially characterized by the need for seasonal replacement of lubricants and further need to replace it during maintenance but today the solutions are developed that allow the operation of up to 1 million km long without the replacement of lubricants in the boxes;

3) Increasing the number of executed functions. Also, this direction involves the transfer of useful functions between the levels (between the modules or between the nodes, or between the basic elements);

4) Increase in relative indicators. In freight wagons, this tendency is manifested, in particular, by the constant search for ways to reduce the container's coefficient (ratio between tare and load carrying capacity) and to increase usefulness of the overall space;

5) Application of more advanced equipment, materials, processes and so forth, which match the modern scientific and technological level;

6) Unwanted effects elimination. For example, the application of devices that prevent unwanted effects during operations (e.g., the bend of the construction under the thermal influence of welding, more advanced aeration devices, etc.);

7) Use of disposable objects. A possible example of such a direction is the introduction of sacrificial elements into the structures of freight wagons. These elements are to damp energy that arise in extreme situations (for example, impacts), due to their own damages, thereby preventing the damage to the main constituent constructions;

8) Block designs that simplify and speed up the assembly and the repair of freight wagons;

9) the use of expensive materials only if necessary in working parts;

10) use of advanced resources.

2.5. How to Apply the Ideal-Orientated Strategy for Freight Wagon Development in the Assessment and the Forecast for Open Wagon Body Evolution

Increasing the perfection degree of freight wagon justifies the need for adaptation of this concept and its special definition, where the peculiarities of freight wagons existence are taken into account. It is proposed that the perfection degree of freight wagon can be represented as integral marker of their efficiency which reflects how freight wagon is approaching to its perfect design, the parameters of which have already been defined, that is, the degree of perfection assesses the perfection of specific samples of a particular family of freight wagons or their constituents. This allows the estimation how the freight wagon designs are approaching the ideal state and compare their individual samples within a single family (for freight wagons, this can be their type-by-cod: according to the model reference book, for example, the open wagons of 606 code are the open wagons with unloading hatches and end walls, as *Models of Freight Wagons* states). In this case, the comparison of freight wagons within the boundaries of one family gives the possibility to compare wagons according to the main indicators of their system useful functions (F_u) and conventionally ignore the most paying factors (ΣF_h), which is explained by their existence within at the same level of the same family.

Being aware of the characteristics of the perfect freight wagon, it is possible to assess the the perfection degree of the studied freight wagon as the magnitude of its approach to the perfect one. We proposed to perform this by calculating the distance between the two points of space that correspond to the ideal freight wagon and the one being compared. In this case, it is expedient to use the formula which defines Euclidean distance between the points, for example, p and q, which corresponds to the length of segment $\overline{pq}$:

$$I(p,q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + ... + (p_n - q_n)^2} = \sqrt{\sum_{k=1}^{n}(p_k - q_k)^2}; \quad (2.3)$$

where $I(p,q)$ – distance between points under the study;

p_k – coordinates or characteristics of the perfect freight wagon;

q_k – coordinates of the studied freight wagon.

Due to the fact that indicators and parameters characterizing the freight wagon are measured in different units of measurement (t, mm, m^3, hr, etc.) or do not have any units of measurement, we suggest to represent them in percentage values to bring them to the same values, where the performance of the perfect freight wagon is characterized as 100%, and the parameters of the studied freight wagon – as the percentage of the perfect. For example: if the perfect freight wagon is characterized by the value of load carrying capacity p_k=P_i=94 t=100 %, then the value of the load carrying capacity of the studied freight wagon is q_k=P_∂=70 t=74.5 %; in this case, if the value of the characteristic of the ideal freight wagon will be less than the value of the one under the study, then the calculation can be made according to the following formula:

$$p_k = P_s^{max} - P_i = 100\%, \tag{2.4}$$

where P_s^{max} – the highest value among the freight wagon models being studied for the dedicated characteristic.

or the studied freight wagon, this value can be written as:

$$q_k = 100 - \frac{100 \cdot P_s}{P_s^{\max} - P_i} (\%). \tag{2.5}$$

Let us consider an example of using the proposed approach with the objective to determine the perfection degree of freight wagon. According to the results of the studies conducted to determine the ideal values of indicators and parameters for the open wagon carrying systems, it was found that the key parameters for evaluation the freight wagon carrying systems are as follows: material consumption (*m*), load carrying capacity (*P*), and loading volume of the body (*V*). These conclusions are supported by the other indicators and parameters of freight wagons, which are listed in the normative document and the reference literature as the requirements for carrying systems. They are estimated axial load, base of the car, length of the coupling axles, design speed, dimensions, 85% of the service lifetime before scrapping the wagon, 90% of service lifetime before major repairs, 95% of service life before the first roundhouse servicing, periodicity of other planned maintenance works, the requirements to the components, namely, to the undercarriage module, coupling equipment module, brake equipment module. All the freight wagons have to meet the values of the above requirements as they are mandatory ones. Therefore, the indicators that can characterize the perfection degree or the efficiency of a certain design of the freight wagon carrying system may be *m*, *P* and *V*. Moreover, knowing the characteristics of the ideal carrying system for freight wagons (m_i, P_i, V_i), one can determine the perfection degree for the carrying systems (*IHC*) of the studied freight wagon (m_∂, P_∂, V_∂) as the distance between the respective points in a rectangular coordinate system (e.g. Figure 3) by the formula as written:

$$I_{HC} = \sqrt{(m_i - m_\partial)^2 + (P_i - P_\partial)^2 + (V_i - V_\partial)^2}. \tag{2.6}$$

Herewith, with the less I_{HC} the studied design is closer to the perfect variant.

As an example how the proposed approach can be applied, let us explain its use when comparing the basic and perspective structures of open wagons of type 606 and the size of 1-BM (the characteristics of which are shown in Table 3.1). In this work we take into account the characteristics of the contemporary freight wagon cars of such models as the following: 18-578, 18-750, 18-781, 18-7020, 18-9771 and18-9810.

In order to visualize the obtained values of I_{HC} for open wagon carrying system under the study, we applied the scatter diagram of the points which correspond to the coordinated for open wagon under the study and those of the ideal wagon with $m_i = 0$t$=100\%$, $P_i = 82.52$t$=100\%$, $V_i = 97.08м^3 = 100\%$ (refer to figure 3). The idealization direction is indicated, the coordinate axes are chosen by the values of material consumption (*m, %*) and load carrying capacity (*P, %*) per the body loading space volume (*V,%*).

Analyzing the data given in Table 2.1, the information presented in Figure 2.4 and the results of the comparison carried out between the perfection degree of the open wagon carrying systems, we suggest that the most close to the ideal is the system of 12-9046 model, produced by PJSC Stakhanov Railway Car Building Works while the most far from the ideal is the system of 132-02 model, manufactured by OJSC "NVK" UVZ". In this case, the following approximate calculations can be made for the quantitative comparison of the percentage difference in the operation efficiency between the designs under the study, namely, carrying systems for open wagons. The service life of the contemporary open wagons has been determined based on the averaged statistical data for the period of 2012-2013. Moreover, it has been found that the minimum effective cost is almost 3 million UAH.

Table 2.1

No	Manufacturer	Model	T, t	P, t	V, m^3	CI, %
1	USSR	1960s	23,2	60	73	104
2	USSR	1980s	24.5	69	76	103.6
3	PJSC KVBZ (Ukraine)	12-7023	23.7	70.3	90	98.7
4	PJSC Azovmash (Ukraine)	12-1704-04	23.5	70	88	97.6
5	PJSC Stakhanov Railway Car Building Works (Ukraine)	12-9046	23	71	85	95.5
6	PJSC Dniprovagonmash (Ukraine)	12-4102	23	71	82	97.1
7	Open wagon of new generation		19.2	74.8	90	79.3
8	Innovative open wagon		13.7	80.3	92	56.2

Accordingly, in order to overcome the service costs for open wagons, the revenue from their operation shall not be less than the specified above amount.

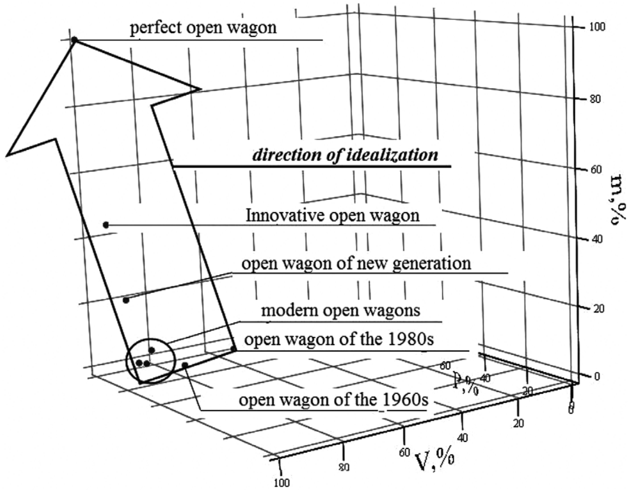


Figure 2.4. Location of the points characterizing the main indicators of the studied open wagons and perfect open wagons

Therefore, we can say that an effective modern design for open wagons is the design which is able to permit income at least of 3 million UAH during their service lives. In connection with the above mentioned and considering the large-scale application of studied open wagons, we can conclude that the latter designs are effective. Thus, the design with the highest degree of perfection can be regarded as that being at the limit of meeting the efficiency requirements and income from its operation is at least 3 million UAH for the period of their service lives. Furthermore, 1% of the perfection degree of the open wagon carrying systems can be represented as I_{CS}= 3 million UAH / 103.5% = 29000 (UAH /%). Hence, it is not difficult to determine the quantitative advantage in the effectiveness of the designs under comparison.

Now, the most promising ways to idealization for modern open wagons and developed forecast for their next generation are considered below.

As per the above mentioned ways for freight wagon idealizing as the most effective directions for open wagons, today the following ways can be used: 1) combining the functions of several elements in the one redistribution way or in the rational one. For example, the promise and efficiency of such a direction has been confirmed by the transfer of the functions of the bottom end wall coping bars of open wagons to the underframe end beam (with coping bars consequent exclusion from the design) which allow reducing material content and decreasing the manufacturing cost for such models of open wagons. The another positive example for the application of this approach is the removal of the lubrication system of bearing units used in the unloading module shaft from the design of open wagon-hopper for hot pellets and sinter. The indicated issue includes several metal-intensive and difficult for maintenance items and also characterized by the need for the additional costs, for example, associated with the lubricant change. The dedicated functions are transferred to the constructively new wear-resistant inserts; 2) elimination of some individual procedures, operations or processes.

The positive direction of this approach implementation is the replacement of rivets for welds, which has been carried out in 80% of the structural units, but there are still some open wagon designs of carrying systems, where rivets are widely used and there are old structural units, which are used by the vast majority of wagon manufacturers (connection of the front and rear stops with the centre grider); 3) as an example of an increase in the number of performed functions may be the addition of a removable cover to open wagon, i.e. the increase in the number of the functions by adding the possibility of cargoes transportations which require the protection from atmospheric precipitation or adding the carrying system to the open wagon with which perform operational loads damping additionally; 4) (5; 7)) extra attention should be paid to the increase of the relative values of open wagon carrying systems since it directly affects their MDF, paying factors and respectively their further evolution. As it has already been noted, the principle indicators of the carrying systems are their own weight, carrying capacity and load capacity of the body. At the same time, the increase in the weight or volume of cargo being carried is possible when the best use of the size of the rolling stock, an increase in the overall dimension space of open wagons or decrease in weight and dimensions of the body module. In terms of dimension limitation, the direction to increase the weight or volume of cargo transported can be represented as targeting the useful application of the load space along with the limiting size of rolling stock volume. The above is illustrated in Figure 2.5. In connection with it, we can conclude that the new generation of open wagons developers is to improve their technical and economic operation parameters at the expense of more and more useful application of the overall space.

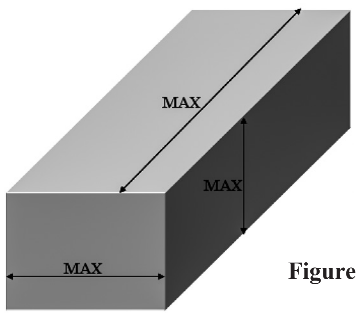


Figure 2.5. Visualization of idealization principle for freight wagons

The contemporary and predicted new generation design schemes for open wagons carrying systems are presented in Figure 2.6, from which it is evident that today's (Figure 3.6 a) body module is located above the module of undercarriage structure, hence there is no space between carriages serving. In the future 3.6 b, the use of the latter is forecasted, which is to increase the useful loading capacity of the body up to 13% and significantly reduce the center of gravity with appropriate improvement on the dynamic properties of the body module. The appropriate decisions have already been proposed and patented. The ultimate goal of idealization for the open wagon carrying systems (Figure 3.6 c) is the combination in the model of MDF body and auxiliary functions of other modules, while simultaneously minimizing its weight, dimensions and volume. In this case, the principle perfection indicator for the open wagon carrying systems can be

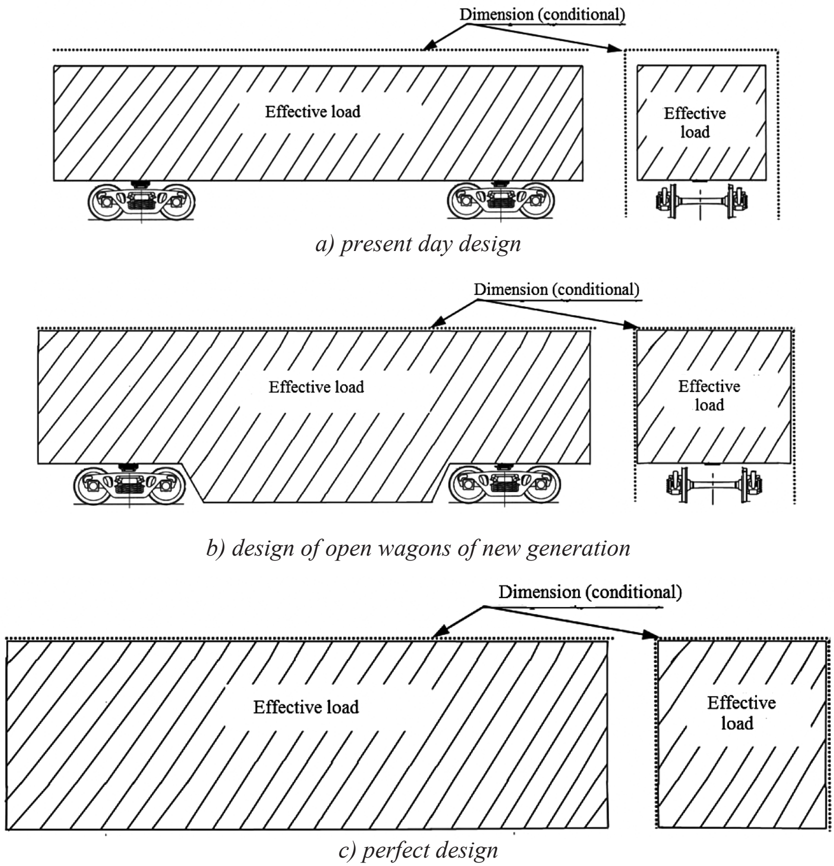


Figure 2.6. Schemes of idealization stages for open wagon carrying systems

considered the coefficient of the material use, which shows the effectiveness or design capabilities in the load bearing or energy absorption that occur in operation when operational conditions; it is determined as the ratio between of maximum operating loads to the weight of the corresponding structure.

It is predicted that the following generations of open wagons are be designed being based on the promising methods for the carrier systems to accept the load. This, the authors are under impression that the next generations are to consistently use the different physical aspects of load bearing, as follows: 1) evenness, where materials utilization rate $\left(K_{mur}^{even}\right)$ is approximately 0.9 from the existing value $\left(K_{mur}^{exist}\right)$: $K_{mur}^{even} \approx 0.9K_{mur}^{exist}$; 2) the approach of the previous use of the loading space, where K_{mur}^{LS} ; 3) introduction of the constituents for distribution energy or energy damping into the open wagon carrying systems when operating loads, for example impacts, where $K_{mur}^{DE} \approx 0.7K_{mur}^{exist}$, 4) the use of electromagnetic emission $K_{mur}^{ee} \approx 0.3K_{mur}^{exist}$, etc.

It should be noted here that by introduction of new composite materials, which meet the demands for the strength at lower metal consumption than steel, at the each of the described above stages we obtain the opportunity for the additional decrease of K_{mur}. The indicated stages of evolution in open wagon engineering systems correspond the law of perfection for the engineering systema and their progress will approach the ideal indicator, where $K_{mur} \to 0$. Due to the fact that the body module is the main module for open wagons (as well as for other freight wagons), it can be stated that the proposed forecast for the following generations of the carrier systems is also a prediction for the development of for freight wagon general structures; 6) elimination of undesirable effects.

Quite promising is currently the mechanism for minimizing or eliminating those financial costs which are spent for the open wagon development, production, and purchases, by introduction the leasing and credit schemes; their general approaches are mentioned in paragraph 8 for freight wagons and also are reflected in the open wagon carrying systems; 9) as the authors we suggest that today it is possible to reduce the costs of manufacturing for freight wagons by defining and production the elements of the existing models from the less valuable steels.

3. METHODS OF MULTIPLE SELECTION FOR NEW RAIL VEHICLE CONSTRUCTIONS

The selection of the variants for the railway rolling stock design [2-7, 11, 21] is a very complex multi-criteria problem. It is very often solved on the base of subjective assessments while notwithstanding enormous preparation work in the form of the analysis on lots of reference and scientific literature not always gives positive result. As any other engineering task, it must be justified in terms of quantity. In this paper, we propose the method of rail vehicle design multiple selection.

This chapter is devoted to the stage of the identification and assessment of the main directions of the thesis research and its task solutions on the base of systematic approach.

3.1. Choice Justification by the Utility Theory Method

The rolling stock is a complex engineering system, the quality of which is determined by many criteria: functions, reliability, cost, energy, resource, temporary character, technology, social factors, environment, etc.

The methods of multi-criteria estimation in the theory of rolling stock design are insufficiently developed today, so there is a problem of creating methods for multi-criteria estimation of alternatives for a complex engineering system.

Let us consider one of the decision-making methods, based on the principles of axiomatic decomposition methods of utility theory.

The development of a driving rolling stock of a new design is a multi-criteria, statistical, non-deterministic task of decision-making. Among the variety of designs, it is necessary to choose the most acceptable one. The criteria for the effectiveness of the driving rolling stock can be as follows:

1. Vertical dynamics coefficient.
2. Horizontal dynamics coefficient.
3. The values of vertical forces and accelerations.
4. The values of the horizontal forces and accelerations.
5. Utilization factor for trailing weight.
6. Total driving force on the track section.
7. The so-called complex criterion for assessing of driving-dynamic characteristics of locomotives, which can be obtained as a vector sum of relative estimates of other coefficients.

Let us consider the task of choosing two variants of the designs for tramcars of LT10 and LT20 produced by Luhanskteplovoz. The values of all the criteria for each variant obtained by calculation in the researches are given in Table 3.1.

Table 3.1

Characteristics of the Tramcar Design Variants to Compare

Variants	Criteria						
	1	2	3	4	5	6	7
1	0.3	0.1	12	0.6	0.4	15	5.2
2	0.25	0.08	8	0.3	0.4	21	5.34

In table 4.1, the best or most preferable and the worst or less preferable criteria values are given. If there are more than two variants, then the best and worst values need to be determined additionally.

The problem must be solved as multi-criteria, static and nondeterministic. This problem is regarded as a multi-criteria one since from the very beginning when choosing the locomotive design, there, as the rule, exist several evaluation criteria and a variety of the design variants. On the other hand, this problem is statistical since information on the dynamics of rolling stock development at the current time is considered to be steady while the changes in the preference order made by the decision maker are to be ignored. The nondeterministic character of the problem is in the fact that at this stage of design development the values of the individual evaluation criteria cannot be determined precisely.

In order to solve the described problem, we can use axiomatic decomposition methods of utility theory. The first step in solving the problem is to check how the axioms of utility theory act under uncertainty conditions. The axioms correctness with decision-making permits us to use the utility theory.

Let us assume that $r^1, r^2, \ldots, r^i \in R$ are multi-criteria or vector assessments of alternatives which are the variants in locomotive design application; $x_1, x_2, \ldots, x_j \in X$ are the set of admissible alternatives.

Herein, r^i serves for vector assess alternatives of x_i unlike r_j - nonvector assessment of i alternative according to j criterion.

If the axioms are true, then there exists numerical function of $v(r)$ for each assessment of $r^i \in R$ in the dedicated valid value of $v(r^i)$, then

$$r^1 \geq r^2 \Leftrightarrow v(r^1) \geq v(r^2)$$
$$r^1 \sim r^2 \Leftrightarrow v(r^1) \geq v(r^2),$$

where $>$ - preference relation;
$\sim$ - indifference ratio.

The next step is the decomposition of the simulated common distribution of *Ф(r/x)*. The required condition of such decomposition is correctness of assumption on probabilistic independence of the criteria within this problem. The condition of probabilistic independence is checked in the following way. It is clarified, whether the decision-maker is able to come to the proper conclusion with the assumed value for r_j criterion of *j* number, provided that he/she knows the value of the other criterion of r_i. This procedure is repeated for all the pairs of $j,\ i \in \overline{1,m}$; and $i \neq j$.

After that, the criteria of independency are to be checked. Let us divide the set of criteria R into two complementing each other subsets of *Y* and *Z*, i.e. $Y,Z \subseteq R,\ Y \bigcup Z = R,\ Y \bigcap Z \neq 0$.

The criteria set of *Y* is independent per preference from complementing subset of *Z*, if the structure of conditional preference is in the space of *Y* at fixed *Z`*, then it does not depend on *Z`*.

1. $Y = \{r_1, r_2\},\ Z = \{r_3,\ r_4,\ r_5,\ r_6,\ r_7\}$.
2. $Y = \{r_2, r_3\},\ Z = \{r_1,\ r_4,\ r_5,\ r_6,\ r_7\}$.
3. $Y = \{r_3, r_4\},\ Z = \{r_1,\ r_2,\ r_5,\ r_6,\ r_7\}$.
4. $Y = \{r_4, r_5\},\ Z = \{r_1,\ r_2,\ r_3,\ r_6,\ r_7\}$.
5. $Y = \{r_5, r_6\},\ Z = \{r_1,\ r_2,\ r_3,\ r_4,\ r_7\}$.
6. $Y = \{r_6, r_7\},\ Z = \{r_1,\ r_2,\ r_3,\ r_4,\ r_5\}$.

On being convinced of independency in terms of the preference, the decision-maker concludes about inter-independency of the criteria.

Then, the additional value function for them can be written as:

$$v[r] = v[r_1, r_2, ..., r_m] = \sum_{j=1}^{m} k_j v_j [r_j],$$

where k_j – scale coefficient of *j* criterion, and we assume the following:

$$\sum_{j=1}^{m} k_j = 1, \quad k_j > \Phi;$$

$v_j(r_j)$ – value function according to criterion r_j, normalized in such a way:

$$0 \leq v_j \leq 1, \quad 0 \leq v \leq 1, \quad j = \overline{1.7}.$$

The probabilistic independence of the criteria allows us to decompose the joint distribution of criterion estimates and represent its density function in the form as given:

$$f(r/x) = \prod_{j=1}^{m} f(r_1/x).$$

To construct the distribution functions, we use the interval method, first applied by Hovord Reif. Below, we submit the order according to which the graphs of the integral functions of the conditional distributions $F_j(r_j/x_i)$ (i.e., the conditional distributions of the criteria values of r_j at $j = 1,N$, if i design variant is assumed at $i = 1,N$-1) are constructed:

– two values of the criterion r_j are determined: the most "optimistic" estimate of $r_j(1.0)$ is the value, which is certainly not to be exceeded under any circumstances in the decision-making problem; the most "pessimistic" estimate of r_j (0.0) is the value of r_j, which is surely to be achieved under any circumstances in the decision-making problem;

– the obtained interval of [r_j (0.0), r_j (1.0)] is divided into two equally probable parts, herein, the decision-maker defines such value of r_j (0.5) at which the probability of the output with the estimate within [r_j (0.0), r_j (0.5)] and [r_j (0.5), r_j (1.0)] is equal if the alternative is x_i.

In order to define scaling coefficients of k_j per all the criteria of r_j, $j = \overline{1.7}$, we use the determined points of equal value through criteria of pair-wise comparison.

Thus, for example, Figure 2.1 shows the point of equal value, observed by the decision-maker for criteria r_1 (vertical dynamics coefficient) and r_2 (horizontal dynamics coefficient).

Point A is equal or indifferent to point B, as they are equally valuable for the decision-maker.

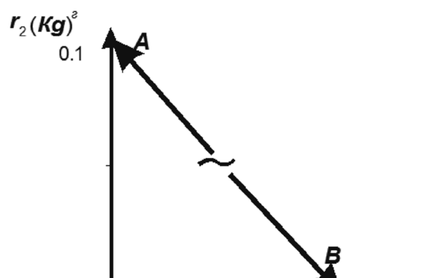


Figure 3.1. Determination of Equal Value Point for Two Criteria

Then, we use the notion of inverse distribution. Inverse distribution α_i for Φ_j (r_j/x_i) is the value of α_i, when as written:

$$\alpha_i = \int_{-\infty}^{r_i(\alpha_i)} \left(r_j / x_i\right) dr_j .$$

Thus, the interval method gives the possibility to define 0.0, 0.25, 0.5, 0.75, and 1.0. They are inverse distributions of $\Phi_j(r_j/x_i)$ at successive divisions of criterion possible value interval into two parts. In case if it is difficult for the decision-maker or the expert to assess the point for dividing any section into equal parts, there may be applied the step-by-step method.

Using α_I fractiles, defined through expertise with the help of interval method, one may construct the graph of integral distribution function of $F_j(r_j/x_i)$.

$$F_j\left(r_j^{\alpha_1} / x_i\right) = \int_{-\infty}^{r_j(\alpha_i)} f\left(r_j / x_i\right) dr_j ,$$

where $F_j\left(r_j^{\alpha_1} / x_i\right)$ are values of integral distribution function (equal to the probability of the fact that the conditional extent of r_j / x_i is the value of r_j criterion at choosing x_i alternative, i.e. i is a design variant) and it takes the values less than $r_j^{\alpha_1} / x_i$;

$f\left(r_j / x_i\right)$ - function of density of distribution probability of R_j / x_i ;

$r_j^{\alpha_1}$ - value of r_j criterion, at which the integral function is equal to probability value of α_i.

Together with the decision-maker, the project developer can choose the specialist, whose statements will be used for construction of the subjective distribution of R_j criterion value. The decision-makers himself/herself can be chosen as the specialist of this kind or the more qualified expert in this sector could be assigned. Here, we mean that sector which is assessed by individual criterion of R_j.

The expert should be interested in cooperation with an analyst-expert in decision-making theory who can organize the procedure in constructing $F_j\left(r_j / x_i\right)$. In this case, he/she must understand that there cannot be any "objective, correct" distribution, otherwise there would be no problem for constructing a subjective distribution, and that the analyst is interested in his/her individual judgments and the respective degree of confidence.

The analyst should be well aware of the simulated decision-making task, in order to tactically direct the collaborative work along the required channel and to help with the necessary materials and publications.

At the next stage of the solution, we construct a graph of one-dimensional utility functions for the certain efficiency criteria by using the method of deterministic equivalent models.

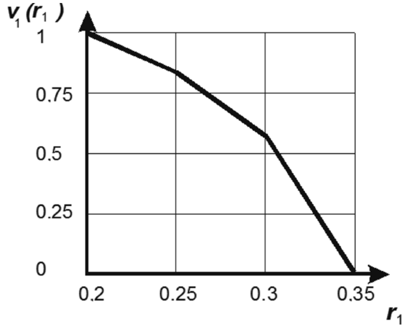


Figure 3.2. One-Dimensional Function of y_1 Criterion Value

Using six graphs with defined point of equal value and additional condition of $\sum_{j=1}^{J} k_j$, we construct the system of linear equations. In this case, it has the following form:

$$
\begin{cases}
k_2 = 0.6k_1 \\
k_3 = 0.65k_1 \\
k_4 = 0.5k_1 \\
k_5 = 0.6k_1 \\
k_6 = 0.62k_1 \\
k_J = 0.8k_1 \\
\sum_{1}^{J} k_j = 1
\end{cases}
$$

We solve the system and obtain the values of the scaling coefficients:

$k_1 = 0.193$; $k_2 = 0.116$; $k_3 = 0.125$
$k_4 = 0.0965$; $k_5 = 0.193$; $k_6 = 0.119$; $k_7 = 0.154$

Consequently, the multidimensional value function may be written as follows:

$$\max_i \overline{v}_i (x_i) = \max_i [\sum_{j=1}^{m} k_j \int_{R_j} v_j (r_j) f (r_j / x_j) dr_j$$

or, according to the results of the solution it follows:

$$v_i(r) = 0.093v_1(r_1) + 0.116v_2(r_2) + 0.125v_3(r_3) + 0.0965v_4(r_4) + \\ +0.193v_5(r_5) + 0.119r_6(v_6) + 0.154v_7(r_7). \quad (3.1)$$

On the base of formulae 2.1, there have been performed the calculations $\overline{v}_i^{боз}(x_i)$ for both variants of design. The values for this case are as below:

$$v_1 = 0.419$$
$$v_2 = 0.624$$

The calculation results bring the conclusion that the second variant is more preferable as compared to the first one, it means that the design modifications are justified.

The research carried out has evidenced that in solving multi-criteria static nondeterministic problems it is expedient to use the utility theory since it obviously takes into account and formalizes the uncertainty of the outcomes and gives a quantitative estimate of the subjective factors. If there are quantitative estimates (experimental, calculated, the results reported in publications), then objective distribution functions can be compiled and show the estimates in a completely objective way.

3.2. Preparation for the Engineering Solution Adoption

The important reserve in increasing the service life of the railway rolling stock, as well as of any other mechanisms and machines is the assessment of the technical condition of the object during the operation and the timely changes in its design.

The calculated loads are usually taken for assessing the driving properties of locomotives, the durability, the reliability, the running qualities, and others; this is explained by the fact that when the locomotive wheel sets and the supports are in the static state, they bear the loads equal to the nominal ones or those having deviations within the normal range. In fact, the stresses occurring in the vehicle elements due to the action of weight load differ from the calculated parameters because of the changes in the dimensions and rigid characteristics of the elastic elements (the change in the wheel diameters, the relaxation processes in rubber-metal elements, etc.).

It should be noted here that the above-mentioned works do not fully regard the issues of actual variation of loads on wheel sets during their operation, quantitative and qualitative reasons for their difference from the design values.

In this paper, along with the study on the causes of the deterioration of the locomotive driving qualities during its operation, we also address the problem of evaluation the influence of these factors on other operational indicators, with the objective to create maintenance load control devices, as well as to adjust static loads and prevent the occurrence of these causes.

The current situation with locomotives and railways requires urgent and serious measures to upgrade and modernize the rolling stock. The modernization of the existing locomotives is needed for improvement on their operational qualities, decrease in wear of both the undercarriage and track, increase in the running period between the maintenance, etc. This entails the development of new designs of locomotives and the devices for their diagnostics, control and repairs.

At the present stage of the science and technology development, the creation of new structures requires vast and tense work as well as the dedicated means, which often leads to the errors in the choice of work direction. The contemporary stage of the design development should be based on knowledge of the fundamental principles of engineering objects formation, patterns of their development and the ways of their updating and provide the appropriate methods and means to be used in their construction.

The knowledge and the application of these principles and laws makes it possible to avoid many mistakes when designing and modifying constructions, as well as performing the pre-project and forecasting studies.

The practice of designing various products allows us to formulate some general principles of design, methodological, logical and mathematical basis for the adoption of engineering solutions.

In this paper with the aim of searching, we used the most common processes, namely, they are as follows:

- definition of problem solving concepts;
- identification of positive and negative effects produced by implementing the various solutions to the problem;
- generation of inventor’s ideas;
- analysis of possible variants and selection of optimal ones.

The stage at which the creative process is embodied includes: expressing the idea in the commonly acceptable form of engineering design; its trial test; the test with further necessary changes and additions; identification of additional possible application areas for engineering solution and expansion of the scope of its implementation.

The analysis carried out at the stage of the creative process idea is necessary as it identifies the central issue or the focal point of the problem, which requires its solution within the current situation with the railway rolling stock.

For the proper choice to be made for the direction of the study, it is necessary to assess the variety of the factors that could influence the results. Moreover, there should be highlighted those factors that influence the nature of the output most strongly while the others could be neglected. This reduces the scope of the research, timing and material costs, as well as simplifies mathematical models that describe the processes or objects under study and allow them to be intensified.

One of the methods used for these purposes at present is the expert judgment method, which involves a survey of experts supported by the analysis on the dedicated sources and production data for ranking all the factors per the degree of their effect on the resulting values. These expert methods are used as prediction methods for making technical decisions.

At present, the solution for scientific, technical and economic forecasting has shown the usefulness of applying expert assessments.

At the stage of preliminary research for the object study, has been carried out a profound analysis on the publication and production reports, which allows us to classify the factors influencing the nature of the process under study and to determine the permissible limits of their change (allowable wear limits for railway wheel tyres, the standard difference in diameters of the wheels in the locomotive car, wheel set, etc.). However, in most cases, it is not possible to assess all the factors to a sufficient degree of objectivity only on the basis of the publication analysis when only one person is engaged, or even simply to highlight all the relevant factors. To do this you need, at least, to create a database of the issue under the study and such database is not available to be taken from the present-day publications. Additionally, as any process is changing within the time, the information on this database should be reviewed and corrected, therefore, it is also necessary to conduct the survey of the experts in this field: research scientists, design engineers, operational specialists, etc. This could be done by developing the appropriate questionnaire and inviting the above mentioned experts to fill it in, evaluating the factors by their degree of influence. In the course of the expert survey, the questionnaire itself can be supplemented, and the results of the survey in the future may serve as the informational source for the database on the issue.

At the preliminary stage, the current situation with the railways has been analyzed and it has showed that both the rolling stock and the upper structure of the track are in the unsatisfactory state while the transportation is inefficient.

We suggest the following questionnaires for the experts to select the most common directions for solving the problem of improving the efficiency of rail transport (refer to tables 3.2, 3.3, 3.4, 3.5).

The questionnaires include two groups of questions:

1. Objective data on the expert profile.

2. The main questions concerning the essence of the problem being solved: they are open, direct, and of a quantitative nature.

The preliminary analysis of the factors has showed their abundance, which could cause difficulties in the process of direct ranking by the experts. Therefore, it was considered that the use a two-stage method of ranking is appropriate.

At the first stage, the ranking of the eight pre-formulated groups or problem factors was performed (refer to table 3.2). The experts could add something to the questionnaire when answering it.

At the second stage, the factors were ranked within problem groups (refer to tables 3.3, 3.4, 3.5). Here, the experts were also given the opportunity to supplement the factors not taken into account before.

In order to simplify the work at the second stage, only those groups that obtained the highest marks with the first expert assessment were left.

Additionally, the group consisted of scientific and engineering workers, who were actively being involved in development and operation of the rolling stock in the CIS countries but mainly in Ukraine.

At the first stage, the problem factors were ranked by the method of averaged evaluation.

According to the results of the survey, a matrix of expert assessments on the factors was compiled. Then the relative value of each factor was calculated separately for each expert.

Table 3.2

Surname ____
Name ____
Middle name ____
Education ____
Position held ____
Work experience in the field of your expertise ______________________________

The Choose of the Direction to Improve the Railway Transport Operation Efficiency Ranking of Factor Groups (Problems)

No	Factors	Estimation
1	Increase in locomotive performance	
2	Increase in the driving force	
3	Reduction in dynamic forces during passing curved sections of the route	
4	Reduction in dynamic forces during passing the straight sections of the route	
5	Reduced wearing of wheels and rails	
6	Reduced fuel consumption	
7	Increase in runs between the repair works	
8	Increase in the value of the driving force	

We suggest that each factor can be evaluated by the degree of its importance at a ten-grade scale, where 10 is the highest grade and 1 is the lowest one.

Table 3.3

Surname ____
Name ____
Middle name ____
Education ____
Position held ____
Work experience in the field of your expertise ________________________

Directions to Increase the Driving Qualities of Locomotives
Ranking of Factor Groups (Problems)

No	Factors	Estimation
1	Redistribution of loads by using elastic elements of different stiffness in spring suspension	
2	Redistribution of loads by using specially dedicated devices	
3	Redistribution of loads through adjusting gaskets	
4	Redistribution of traction moments on wheel set	
5	Increase in the locomotive power	
6	Increase in axial load	
7	Application of abrasive materials in contact	
8	Application of support-frame of the driving motor	
9	Application of balanced spring suspension	
10	Development of new antisked systems	

Each factor can be evaluated by the degree of its importance at a ten-grade scale, where 10 is the highest grade and 1 is the lowest one.

Table 3.4

Surname ____
Name ____
Middle name ____
Education ____
Position held ____
Work experience in the field of your expertise ________________________

Directions to Increase the Dynamic Qualities of Locomotives
Ranking of Factor Groups (Problems)

No	Factors	Estimation
1	Redistribution of loads by using elastic elements of different stiffness in spring suspension	
2	Redistribution of loads by using specially dedicated devices	

No	Factors	Estimation
3	Redistribution of loads through adjusting gaskets	
4	Reduction in axial loads	
5	Application of devices for locomotive insertion into curved route	
6	Radial arrangement of wheel set	
7	Forced body tilt	
8	Separately rotating wheels	
9	Application of support-frame of the driving motor	
10	Reduction in unsprung mass	

Each factor can be evaluated by the degree of its importance at a ten-grade scale, where 10 is the highest grade and 1 is the lowest one.

Table 3.5

Surname ____
Name ____
Middle name ____
Education ____
Position held ____
Work experience in the field of your expertise ________________________________

Directions to Decrease Locomotive Wheel Wearing
Ranking of Factor Groups (Problems)

No	Factors	Estimation
1	Locomotive redistribution by the use of elastic elements of different stiffness in spring suspension	
2	Locomotive redistribution by the use of specially dedicated devices for redistribution of loads	
3	Locomotive redistribution through adjusting gaskets	
4	Redistribution of traction moments on wheel set	
5	Application of flange and rail lubricating devices	
6	Application of devices for locomotive insertion into curve paths	
7	Radial arrangement of wheel set	
8	Separately rotating wheels	
9	Development of new antisked systems	
10	Development of the sand feeding system able to decrease the amount of the sand supplied into the contact area	
11	Development of new wheel and rail profiles	
12	Increase in the hardness of the wheels and rails	

Each factor can be evaluated by the degree of its importance at a twelve-grade scale, where 12 is the highest grade and 1 is the lowest one.

$$w_{ij} = \frac{x_{ij}}{\sum_{i}^{n} x_{ij}}, \tag{3.2}$$

where x_{ij} is estimation *I* factor, given by *j*-expert, *n* is the number of the factors.

The averaged factor evaluation:

$$W_i = \sum_{j}^{m} w_{ij}, \tag{3.3}$$

where *m* is the number of the experts.

Based on W_i, the diagram of the group ranks has been built (Figure 3.3).

In order to check the experts' opinions for the consistency, the coefficient of concordance has been calculated.

The coefficient of concordance *W* is in accordance with Kendall formula:

$$W = \frac{12S}{m^2\left(n^3 - n\right)}, \tag{3.4}$$

where *S* is sum of squares of deviations from the mean value of the summarized ranking series, then:

$$S = \sum_{i}^{n}\left(\sum_{j}^{m} a_{ij} - 0,5m\left(n+1\right)\right), \tag{3.5}$$

where a_{ij} is the ranking of *i*-factor, given by *j*-expert

For the group factors *W*=0.608, *W* is less than one, therefore we can say that the agreement in the expert's opinions in not occasional.

The value of *W* coefficient is checked by $\chi 2$ criterion, then we write:

$$\chi 2 = m(n-1)W. \tag{3.6}$$

Table 3.6

Ranking of Factor Groups (Problems)

No	Factors	Estimation
1	Increase in locomotive performance	0.130
2	Increase in the driving force	0.82
3	Reduction in dynamic forces during passing curved sections of the route	0.48
4	Reduction in dynamic forces during passing the straight sections of the route	0.118
5	Reduced wearing of wheels and rails	0.131
6	Reduced fuel consumption	0.180
7	Increase in runs between the repair works	0.154
8	Increase in the value of the driving force	0.158

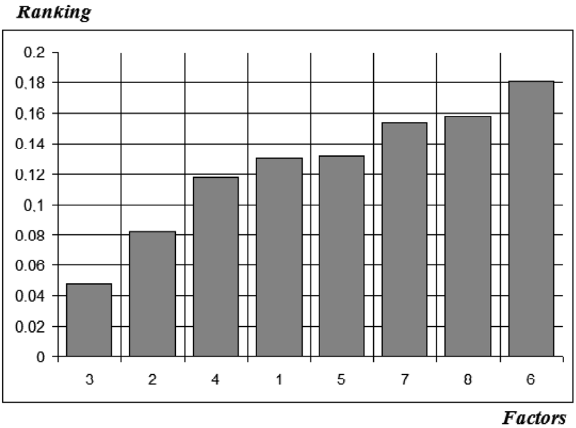


Figure 43.3. Chart of Group Ranking

If $\chi 2 = 17.021 > \chi 2$ table=14.07, chosen for the value level of 95%, then the hypothesis of the consent of experts is acceptable.

The ranking results enable us to point out the following most significant problems: *Reduced wearing of wheels and rails*; *Increase in the value of the driving force*; and *Reduction in dynamic forces*. The indicated issues are closely related to the problems of *Increase in runs between the repair works* and *Increase in locomotive performance*. Thus, the second stage saw selection of the most important factors in the groups, they are as follows: *Increase in the driving force*, *Reduced wearing* and *Increase in dynamic values* (refer to tables 3.3, 3.4, 3.5). Within the each group, the factor ranking has been carried out per averaged estimation (3.2), (3.3). The further comparison between all the factors was carried out with ranking by combined method.

First, the averaged estimation for the factor was defined per the comparable.

$$q_k = \frac{W_i}{\sum_k^p W_k^1}, \tag{3.7}$$

where W_i is estimation group factor (4.3);
W'_k is estimation within the group;
p is a number of the factors in the group.

The sum is accepted as the final estimate:

$$Q_k = W_i + q_k. \tag{3.8}$$

Obtained by the indicated way, the estimation factors are given in table 3.7

One and the same factor could be in the different groups because it simultaneously influences the different parameters of the locomotive. Therefore, the estimations of these factors underwent summation in the different groups.

The factors, grounded on the vertical loads redistribution principle, have the influence on driving, dynamics and wearing. However, their impacts are different on the three of the relevant issues: 1) the value of the dynamic forces within the system of "locomotive-rail"; 2) the degree of the driving force utility; and 3) wearing. Thus, the resulting estimates of these factors after their analysis were defined as the sum in the first group of "Influence on Driving Parameters" and the third group of "Influence on Wearing".

The concordance coefficients for each group of the factors were 0.848, 0.808 and 0.735, respectively.

The Chart of Ranking is given in Figure 3.4.

The verification per $\chi 2$ criterion has showed that it is equal to 30.545, 29.073 and 32.3466, respectively. These values are greater than their table value of $\chi 2$ (table value= 14.07 for 95% of the significance level) and this permits us to say that the consistency of experts' opinions is observed across all the factor groups.

The analysis on the results of the experts' survey has shown that the most effective actions to enhance the efficiency of railway locomotive performance are those based on redistributions of the vertical loads and traction moments. The tribute is also paid to flange lubricating devices, radial arrangement of wheel set, application of device for locomotive insertion into curve routes, application of support-frame of the driving motor and separately rotating wheels. This means that they are the actions, which are used at designing the latest transportation means.

Table 3.7

Summarized Table of Ranking Factors

No	Factors	Estimation
1	Redistribution of loads by using elastic elements of different stiffness in spring suspension	0.43538 (0.35)
2	Redistribution of loads by using specially dedicated devices	0.44788 (0.363)
3	Redistribution of loads through adjusting gaskets	0.45994 (0.3704)
4	Redistribution of traction moments on wheel set	0.3704
5	Increase in the locomotive power	0.1604
6	Increase in axial load	0.1559
7	Application of abrasive materials in contact	0.1561
8	Application of support-frame of the driving motor	0.255
9	Application of balanced spring suspension	0.1628
10	Development of new antisked systems	0.35

No	Factors	Estimation
11	Reduction in axial loads	0.09283
12	Application of devices for locomotive insertion into curve routes	0.28859
13	Radial arrangement of wheel set	0.29158
14	Forced body tilt	0.08954
15	Separately rotating wheels	0.28485
16	Application of flange and rail lubricating devices	0.1966
17	Development of the sand feeding system able to decrease the amount of the sand supplied into the contact area	0.1842
18	Development of new wheel and rail profiles	0.1874
19	Increase in the hardness of the wheels and rails	0.1857
20	Reduction in unsprung mass	0.0834

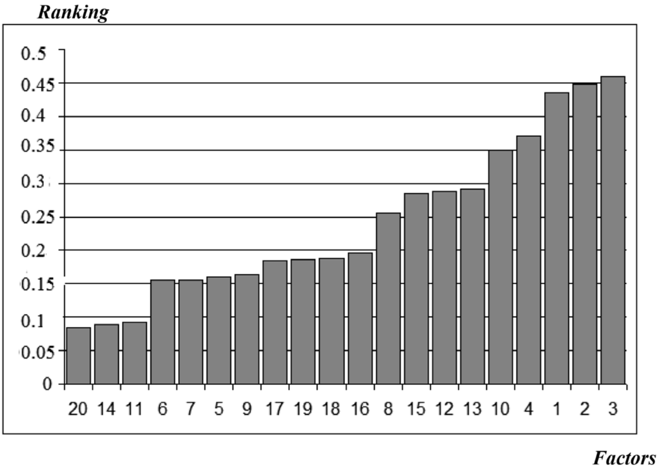


Figure 3.4. Chart of Final Ranking

1. The estimation should be carried out as the maximum objective one, therefore the quantitative estimation is necessary.

2. Both for the preliminary estimation, which applies mainly the calculated data, and for the final estimation, where apart from the calculated data the trial test results are also available, the method grounded on the principles of axiomatic decompositive methods is suitable.

3. In order to make the engineering solution choosing from the wider range of the research directions and under conditions of greater uncertainty, the estimation can be made by the experts' assessment.

4. THEORETICAL BASIS OF PARAMETRIC SYNTHESIS OF WAGON CARRYING SYSTEMS

The objective of this chapter is generalized presentation of theoretical fundamentals for the wagon component optimization design [21] and practical means of its implementation. In order to identify the freight wagon components, at the account of which it is reasonable to improve technical, economic and operational parameters for freight wagons, the two principle scientific approaches can be applied.

The first approach is oriented at exploratory researches, focused on identification of such configuration for the design and the material that is able to provide strength characteristics not lower than in the existing design of wagon-analogue but with less material consumption and cheaper production prime cost.

The second approach is more advanced, as it is focused on identification and effective application of calculated strength reserves with the relevant reduction in energy and material consumption spent for production and repairs of the component under study. Additionally, strength reserve in this paper is defined as the relation between the obtained maximal operating characteristics of strength and their allowable values. For implementing the second direction, it is required to carry out the multimode research on the element operation within the wagon-analogue in respect to the emerging operational loads in order to identify the estimated power reserves. Moreover, the research is to be carried out with consideration of all the possible regular and emergency situations at the stages of the wagon life cycle. Currently, it is reasonable to perform the mentioned through the research on finite element adequate estimation for the relevant model of a wagon. At identification of the estimated structure strength reserves, the rational strength parameters are to be computed. They are also taken into the consideration for the first approach and serve as limitations at the further design stages. The development of the identification procedure for the means to form the carrying reserves of the general wagon structures and their components is based on the principle that the strength reserve of the general structure and the unit is determined by minimal strength reserve of their components.

To formalize the procedure according to which various profiles can be introduced as the components of the freight wagon carrying systems, it is reasonable to apply the developed mathematical model or the selection rule. Its features are focused on the complex improvement on the structure through modernization of its individual components and the criterion of minimal material consumption, defined in terms of technical and economic parameters:

$$\begin{cases} TF: \\ m = f(n_1, n_2 \ldots n_k) \to \min \\ RAS: \\ [\sigma]^i \geq \sigma^i_{\exp} = f(n_1, n_2 \ldots n_k); i = \mathrm{I}, \mathrm{II}, \mathrm{III} \\ [\sigma]^{imp} \geq \sigma^{imp} = f(n_1, n_2 \ldots n_k); \\ \left[N_y\right] \geq N_y^{\exp} = f(n_1, n_2 \ldots n_k); \\ \left[N\right] \geq N^{\exp} = f(n_1, n_2 \ldots n_k); \\ RPS: \\ n_{i\min} \geq n_I \geq n_{\max}; I = [1, k] \end{cases} \quad (4.1),$$

where superscript *exp* stands for *operational*. The target function (*TF*) is material consumption (*m*) of the introduced element, which is the main criterion of optimization. The material consumption depends on variable geometrical parameters $(n_1, n_2 \ldots n_k)$. *K* is changed due to its structural features and is identified in the region of feasibility (*RAS*), while RAS itself is singled out from the area of feasible solutions (*RPS*) with the help of the following functional restriction:

$$\begin{aligned} &[\sigma]^i \geq \sigma^i_{\exp} = f(n_1, n_2 \ldots n_k); i = \mathrm{I}, \mathrm{II}, \mathrm{III} \\ &[\sigma]^{imp} \geq \sigma^{imp} = f(n_1, n_2 \ldots n_k); \\ &\left[N_y\right] \geq N_y^{\exp} = f(n_1, n_2 \ldots n_k); \\ &\left[N\right] \geq N^{\exp} = f(n_1, n_2 \ldots n_k) \end{aligned} \quad (4.2)$$

Let us consider the strength in the first ($[\sigma]^{\mathrm{I}}$), second ($[\sigma]^{\mathrm{II}}$) and third ($[\sigma]^{\mathrm{III}}$) calculation modes. In accordance with [12-17, 19, 22, 24], we take into account the following restrictions in case of an impact ($[\sigma]^{imp}$): hardness [f], durability [N_y] and fatigue endurance [N]. The restricting parameters also depend on variation of geometrical parameters $(n_1, n_2 ... n_k)$, then, the area of feasible solutions is formed by variations of the changeable parameters $(n_1, n_2 ... n_k)$:

$$\begin{aligned} &n_{1\min} \geq n_1 \geq n_{1\max}; \\ &n_{2\min} \geq n_2 \geq n_{2\max}; ... \\ &n_{k\min} \geq n_k \geq n_{k\max} \end{aligned} \qquad (4.3).$$

The restrictions of the area of feasible solutions are defined by the structural or operational features of the wagon component being introduced.

Furthermore, for freight wagon carrying system design, it is reasonable to use the moment resistance of the relevant cross-sections ([W_X], [W_Y], [W_Z]) as functional restrictions.

To summarize all the above, we show the procedure of design optimization for the wagon components, which may generally be presented in the form of the chart (refer to Figure 1).

One of the key moments of the suggested methodological complex is the identification of the estimated strength reserves. In a general case, the relevant procedure has 4 main stages (refer to Figure 2). Thus, the first stage embraces the performance tests on the full-scale samples of wagon design with the objective to identify the actual values of mechanical stress in the control points, to develop the computed finite element model, and to conduct computer simulation of those operating modes, which are decided to be the most important for the research. At the next stage we choose the carrying elements for the research and decompose them into separate sections. The areas of the sections or their number are selected as dependent on the required depth of the engineering study: the less their size, the higher the result accuracy. The second stage is devoted to identification of the initial or provided by design strength reserve at individual structure sections, after that, we choose the smallest of them through comparison, this allows the possibility to identify the initial strength reserves of the structure under research in general.

Due to the fact that operational equivalent stresses σ_{eq} are defined as the correlation between the sum of equivalent moment (M_{equiv}) and strength characteristics ($W_{X(Y,Z)}$), but value M_{equiv} is said to be almost constant, then one can make the conclusion that the value of σ_{equiv} is directly proportional to the values of moment resistance of $W_{X(Y,Z)}$. This means that, the latter may be used as the main strength characteristics of the profile. Thus, the assessment on the strength properties of the carrying reserve of the freight wagon components is narrowed to the assessment of their moment resistance reserves. For this purpose,

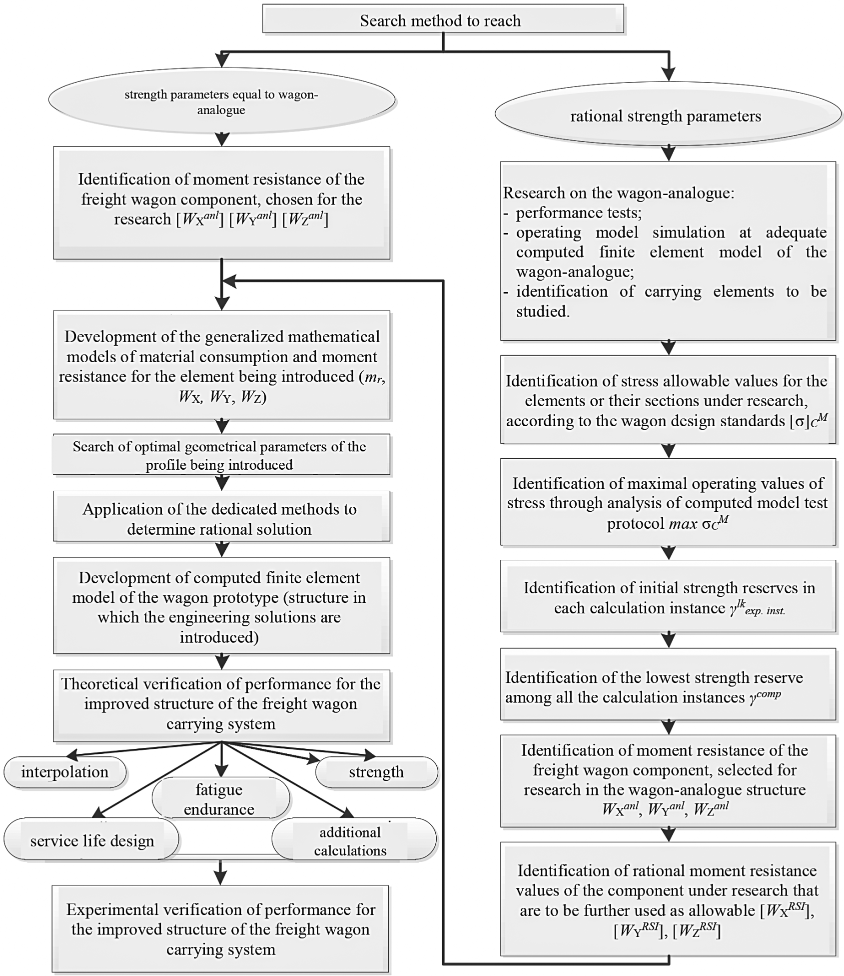


Figure 1. Chart of Profile Introduction into the Freight Wagon Carrying Systems

at the third stage we perform the works on identification of moment resistance allowable values of the component under the study both in general $[W^{comp}_{X(Y,Z)}]$ and individually by sections $[W^{lk}_{X(Y,Z)}]$. Eventually, depending on the research aims we carry out the identification of And/Or application of the computed strength reserves of the structure (cell 4, Figure 4.2) And/Or assessment of the operation (cell 5). In the latter case, there should be identified the mathematical models to describe the change of the moment resistance and material consumption of the wagon carrying elements under research depending on the variation of their

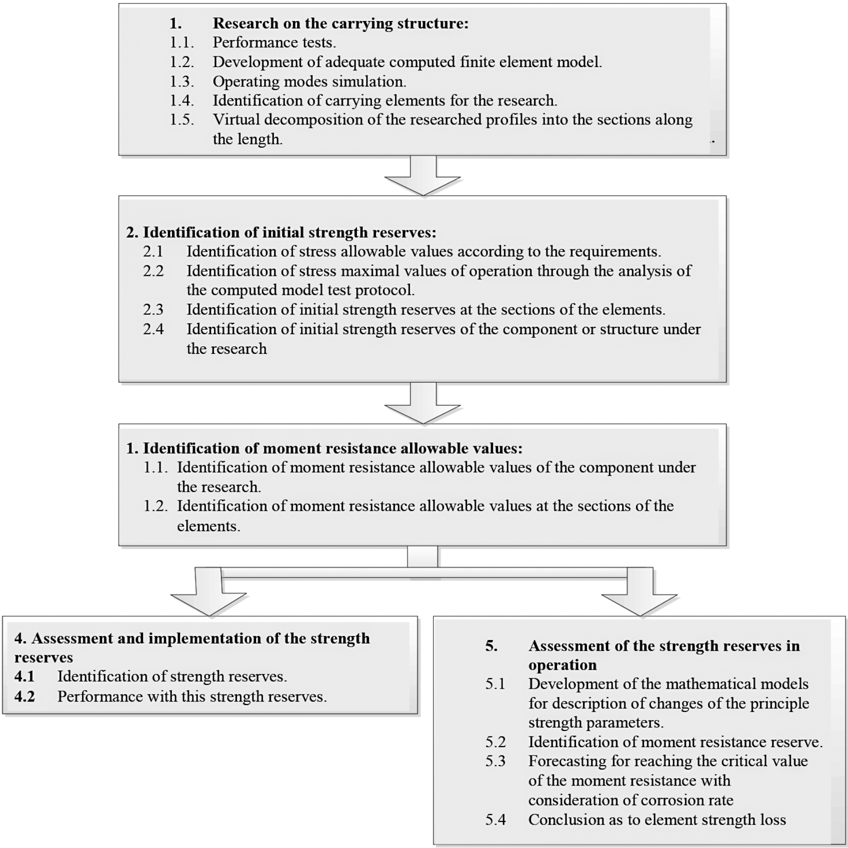


Figure 2. Estimation Algorithm of Carrying Reserves of the Freight Wagon Components

geometrical parameters. In addition, there should be also identified the structure strength reserves for individual section of the component ($\gamma^{res}_{W^{comp}_{X(Y,Z)}}$) and its total value ($\gamma^{res}_{W^{lk}_{X(Y,Z)}}$); further, the scientific forecasting is expected to indicate the time when the moment resistance reaches the critical value and to consider the corrosion rate.

The complex improvement on the freight wagon structure through individual modernization of its components is a complex scientific and technical issue. Its solution requires automation of the identification procedure for the estimated strength parameters as well as for the process of structure synthesis with optimal characteristics in general. This is possible to achieve provided that the development of the relevant scientific tools has been carried out and they are implemented on

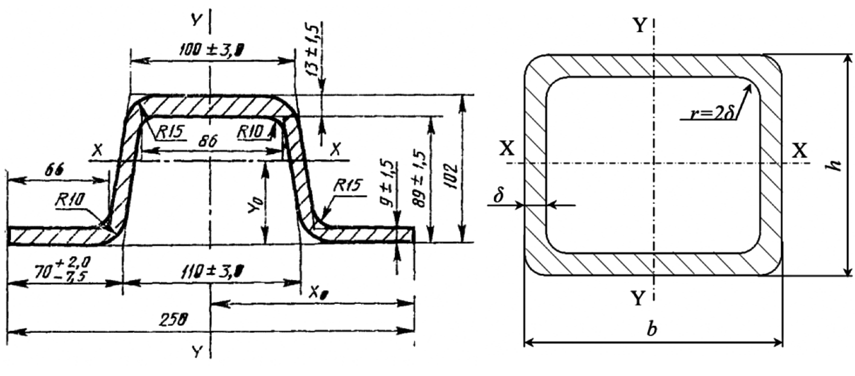
PC applications. The authors propose to solve this issue through the algorithms developed for determining the rational geometrical parameters for the profiles with the help of one of three methods, namely they are:

- Excel of standard Microsoft Office suite;
- integration approaches, based on application of the functions of Maximize and Minimize of all-purpose MathCAD software suite;
- application of the developed original authorial software programs for work with three-factor generalized mathematical models.

As an example of practical implementation of the mentioned three methods below, there is provided the information on their application for identifying the rational geometrical parameters of the open wagon stakes and flanges. The same components within the wagons-analogues are made of specific and, consequently expensive omega-profile (Figure 4.3 *a*), and we suggest to make them of more promising material of rectangular tubes (Figure 4.3 *b*).

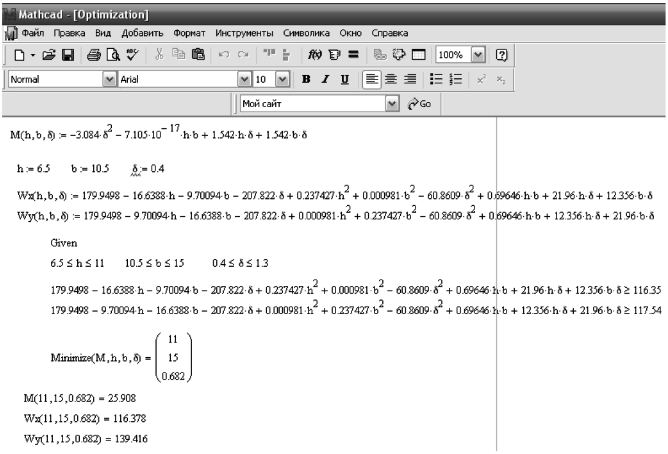
The optimal values for such an improvement are obtained first through Microsoft Excel. This is performed by the step-by-step method sorting of all the possible solutions within the specified range of feasible solutions area with further elaboration within the feasibility region. The similar results (refer to Figure 4.4) of optimal characteristics for wagon stake profile are obtained in calculations with application of functions of Maximize and Minimize of MathCAD suite.

It should also be noted that both approaches described above are oriented for application of widely used software complexes, commonly applied by the engineering services at the most of enterprises and without special requirements of the additional investments (purchase of special software and relevant training for the personnel).

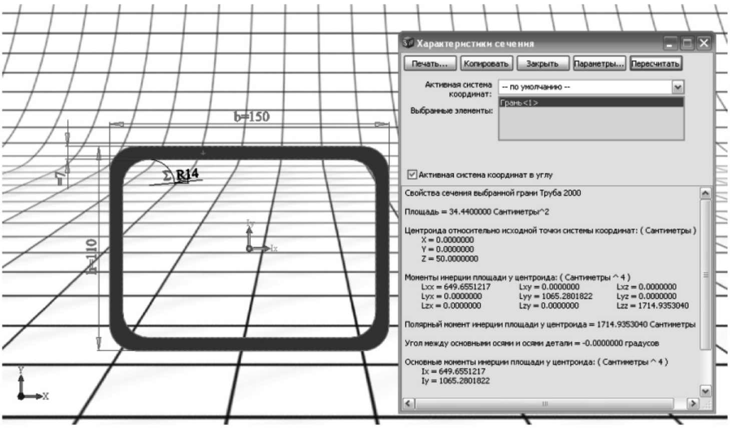


a *b*

Figure 3. Profile cross-sections: *a* – wagon stake; *b* – rectangular tube



a



b

Figure 4. The Results of the Exploration Work with MathCAD:
***a* – calculation unit; *b* – computer model**

As the alternative approach to optimal parameters identification, able to ensure the minimal material consumption of the structure within the required strength and structural restrictions, there can be applied specially developed software. This software complex (refer for the example to a graphic interface in Figure 4.5) first identifies three-factor generalized mathematical models to describe the change in the freight wagon component parameters under the research (material consumption and axial moment resistance) as dependent on the variations of the geometrical parameters (for example, height, element cross-section width and thickness of the sheet, from which it is produced).

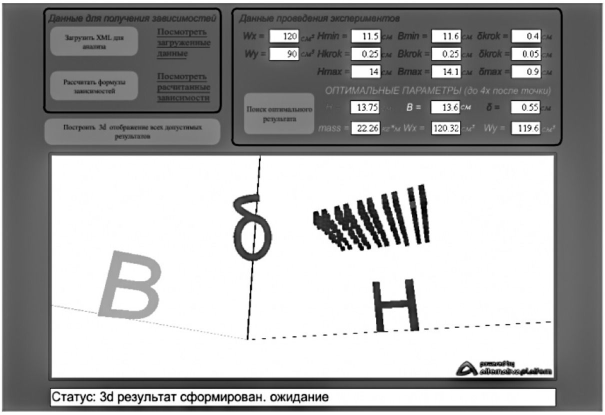


Figure 5. General View of the Working Area of the Software with Solution Visualization

In case of the analytical identification of optimal parameters, the software implements the proposed algorithm and identifies optimal variant of correlation between the characteristics under the research. Herein, the complex also gives the possibility to visualize the variants, included into the region of feasibility, and defines the optimal result, based on 3D modelling within the spatial coordinates. However, the provided above results of the researches show that independently from the applied tools, the comparison of the experimentally obtained characteristics with their calculated values confirms the effectiveness of all the described above methodological approaches.

Eventually, the application of the proposed methodological complex makes possible profound modernization of the existing models of freight wagons (refer to Figure 4.6 *b, c*) and allows the development of the new competitive samples (Figure 6 *a*).

In addition, the application of the proposed and described above methodological approaches allows the possibility to calculate and to develop the family of the advanced models of the freight wagons (refer to Figure 4.7).

The introduction of the reported research results permits the possibility of significant improvement on engineering, economic, and operational parameters of the freight wagons. Considering the fact of the mass-scale production (PJSC Ukrzaliznytsia alone uses more than 160,000 units), this promises the forthcoming economic effect. The proposed algorithm may also be used for the solution of other relevant optimization tasks on the base of the generalized mathematical models.

a

b

c

Figure 6. Models of freight wagons, developed and modernized with application of methodological complex of optimized design:
***a* – 12-9904 and 12-9904-01 models of open wagons; *b* – 12-9745 model open wagons; *c* – 20-9749 models of hopper**

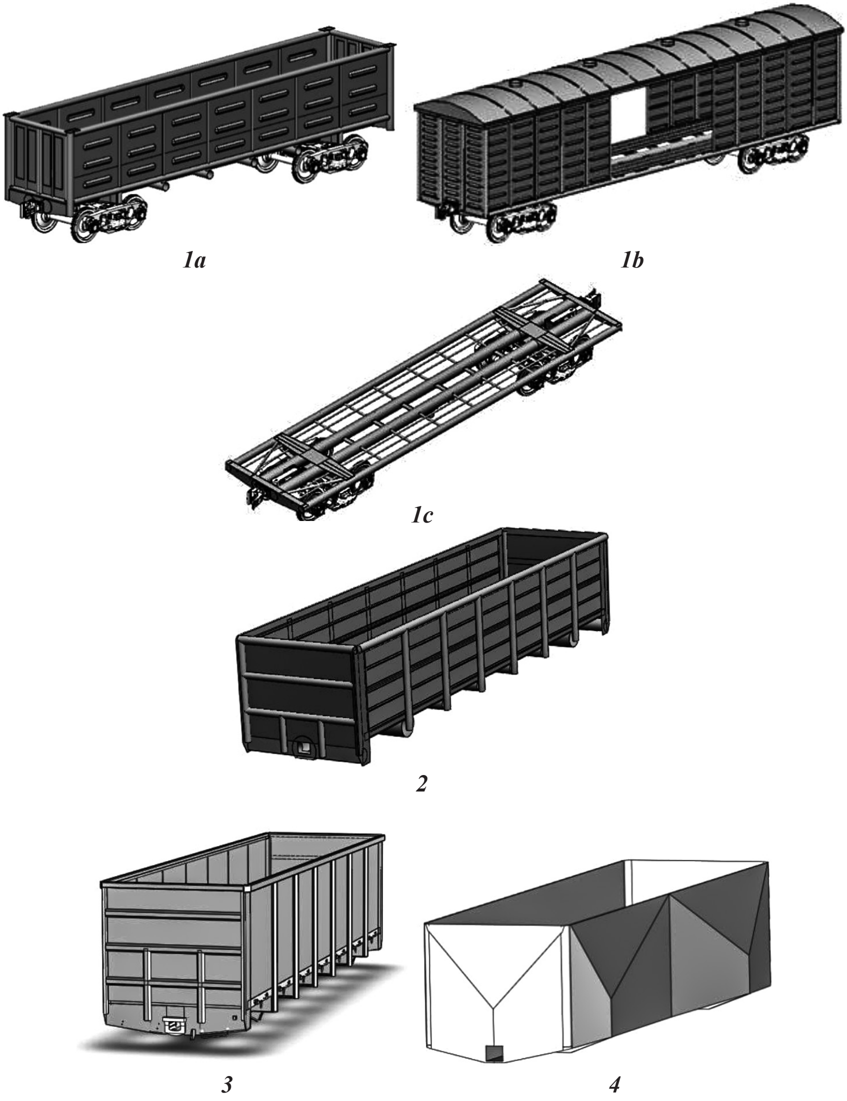


Figure 7. The Promising Designs of the Carrying System of Freight Wagons Developed by the Methodological Complex of Design Optimization.
1 **– Round Tubes Application in the Design:** ***a*** **– open wagon;** ***b*** **– covered wagon;** ***c*** **– car platform;** ***2*** **– D-Shaped Tubes Application in the Design;** ***3*** **– Hexagonal Profiles;** ***4*** **– Carbon Composite Materials**

5. SCIENTIFIC BASIS FOR THE FORMALIZED DESCRIPTION OF FREIGHT WAGON CONSTRUCTIONS

5.1. The Description of Options for Freight Wagon Designs

Currently, the concerned domestic research and production companies along with well as the organizations working in the sector of transportation are increasingly directing their scientific and research activities as well as their research and design projects towards the competitive models of freight wagons, which could possess the advanced technical and economic operation parameters. The minutes of PJSC Ukrzaliznytsia Technical Council meeting dd 30.09.2015 evidence the necessity to develop of innovative freight wagons and describe the basic requirements for their design. On the one hand, the development of new freight wagon model is analogue-oriented and requires considerable monetary and time investments. The successfully completed project of new wagon model is forecasted to result in a rather individual technical project and this consequently does not permit the opportunity to cover the constantly increasing needs of the participants in their service life. On the other hand, modernization or modifications for the freight wagon of specific model require additional procedures: alternation and approval of design documentation and technological specification, appropriate testing and certification, the physical changes or adaptation. Moreover, the related re-equipment of the production base requires large-scale additional investments and time. However, the existing conditions of the transport market require from the wagon manufacturers and those who are engaged in transport services the urgent response to the constantly changing requirements of the customers for new wagons or transportation services. Such a situation stipulates the reasonability to develop the freight wagon projects in a way to allow the opportunity of their on-line adaptation to special conditions of the customer and this requires the improvement on methodological basis of freight wagon design. When developing the freight wagon project with the wide range of possible designs, the description of their variations may serve as the scientific grounds for such a project [18, 21, 24] in the form of integrated representation of the design variations of the system components. In its turn, is can provide the possibility of on-line combining, developing new or reviewing the existing designs and functional schemes. In the future, such a practice is able to become the methodological basis for engineering projects to be approved for introduction of freight wagons with possibilities of their on-line adaptation to the individual requirements of the customer (for example, situational conditions of the metal products market, production and operational conditions for the wagon manufacturers, etc.) and, consequently, is expected to enable a appreciable reduction in the resource consumption and applying contemporary computer tools for the researches and the design projects in the area of the transport structures. Furthermore, the results of the analysis on the vast range of scientific and reference sources, associated with issues under the study, have showed the absence of information on the solution of such important and up-to-date scientific and practical problems as indicated above.

5.1.1. General Principles of Design Variants Description for Freight Wagons and their Components in the Form of Structural AND-OR Trees

The proposed methods are based on the following principles: modularity, hierarchy and variation. These principles are fully reflected in the variation module-hierarchy model of the freight wagon, that is the most informative when it is reflected in the form of AND-OR tree, which defines the functional elements of the freight wagons and their structural features. Moreover, the mentioned model is a visual and convenient means of compact presentation and storage of information on the existing vast funds, as well as on the patentable designs of the freight wagon components. In certain cases, it may be presented in the form of the relevant morphological table.

For the description of a freight wagon structure, it is convenient to use the relevant AND tree, which is the aggregate of apices (graphically depicted as dark circles) and ribs that connect them. The description of the physical structure is divided into hierarchical levels, while the apices on each level represent the dedicated components of the freight wagon under consideration. The single apex of the zero level is called the root one; it stands for the freight wagon being designed. It is connected through the ribs with the apices of the first level, which, in their turn, are connected with the apices of the second level (relevant component parts). Finally, the apices of n-level or leaves correspond to the basic elements, indivisible into the components. The use of AND-OR tree is reasonable if we need to group the information on several structures of the freight wagon and their components into a single description. Unlike the AND tree, AND-OR tree possesses each neighboring level, composed of apices of different types: OR apices are light circles and AND apices are dark circles. The use of OR apices in the descriptions of the freight wagons permits us to take into account possible alternative projects and design solutions for freight wagon components. In AND-OR tree, developed for the freight wagon structures, it is reasonable to point out the modules, the units, the basic elements and the structural features. The depth of the profound study to create the AND-OR tree is defined by the relevant targets.

The structure of the combined AND-OR tree developed to describe the freight wagon is of the following order: 1) the multitude of the selected designs for which the module-hierarchical models (AND trees) is developed; 2) the multitude is divided into several groups, each is composed of the elements, the closest in terms of their structure and function; 3) the separate elements are taken for each group, they refer to the first hierarchical level and their own AND-OR trees are constructed for them, where AND apices (dark circles in the chart) connect the obligatory elements and design features, while OR apices (light circles in the chart) connect the alternative elements and features. Herein, the elements and features that repeat in the AND-OR tree are specified only once. AND-OR trees, constructed specially for some components of the freight wagon, are combined in one AND-OR tree.

In general case, at the development of AND-OR tree for a certain freight wagon it is required to study its project, to define main functional elements and their significant structural features:

1. Shape configuration (in the chart it is marked with letters *Ф*) of profiles or designs that may be supplemented with the characteristics (moment resistance, weight, parts, units, etc.).

2. Structural materials (letters *KM* in the chart), including steels that may be used and their specific properties (yield strength, fatigue strength, corrosive resistance, etc.)

3. Production (letters *CB* in the chart), that may include weld joint, bolt connection, assembly welded joint, casting, elements solid along the length, splice, rolled elements solid along the cross-section, forged elements.

Upon development of the combined AND-OR tree, it is required to check the correctness of its structure. Herein, one should take into account the fact that

AND-OR tree must ensure the storage of all the known engineering solutions of the relevant freight wagon type. Its checking is recommended to perform by taking any model of the relevant type of the freight wagon in the form of AND tree and judging, whether it is possible to obtain it from the combined AND-OR tree through exclusion of OR apices.

5.1.2. Variants Description for the General Purpose Open Wagon Center Sill

The implementation of the proposed in the previous chapters method is presented below as an example of AND-OR tree (refer to Figure 5.1), developed for the center sill of general purpose open wagons. Its development is based on the actual data. The specified selection of the supporting element is explained by the exclusive bearing importance of center sill in the structure of open wagons. The elements of the AND-OR tree indicated in figure 5.1 are interpreted in table 5.1.

From figure 5.1, it is obvious that the unit-forming element of center sill (B_{1121}) is pointed out as crucial within the structure of the general purpose open wagon design at level 3 of the combined AND-OR tree while at its level 4 it is divided into OR branches per the design technique (CB_{1121}, CB^{1}_{1121}). Herein, in case of rivet connection CB_{1121}, the rivets of B_{11218} and B_{11219} are included into the wagon. In the neighboring branch, the following elements (B_{11211} beam, B_{1121} binding course, B_{11213} center plate, B_{11214} strip, B_{11215} front support, B_{11216} rear support, B_{11217} anti-wear strip) are singled out.

The binding course (B_{11212}) may be of various shapes indicated through Φ_{11212} and Φ^{1}_{11212}. In addition, the center plate (B_{11213}) may be cast (CB_{11213}) or assembly-welded (CB^{1}_{11213}) formed by the elements of B_{112131}, B_{112132}, B_{112133}, B_{112134}, B_{112135}. (table 5.1.). Level 5 of the regarded description is presented by the components of level 4 objects. Thus, there is defined OR bush that presents the variants of center sill cross-section design, namely: advanced rolled stock solid along the cross-section (CB_{11211}), shown in figure 4.2 *c* and the existing assembly welded variant (CB^{1}_{11211}) illustrated in figure 5.2 *a*. Furthermore, in the course of development of the AND-OR tree, there has been found the patentable design of the center sill made of the cut sheets (refer to figure 5.2 b). The assembly-welded variant (CB^{1}_{11211}) for the center sill provides top sill (B_{112112}) and bottom sill (B_{112113}) to be distinguished within the structure as shown in figure 5.2 a and figure 5.3. In addition, there is also found the feasibility to have the center sill solid along the cross-section (B_{112111}) made from different steel grades (KM_{112111}, KM^{1}_{112111}). In addition, at level 5, there is also singled out the possibility of sill design with rivet connection (CB_{112112}) for manhole cover bracket and welded one (CB^{1}_{112112}),

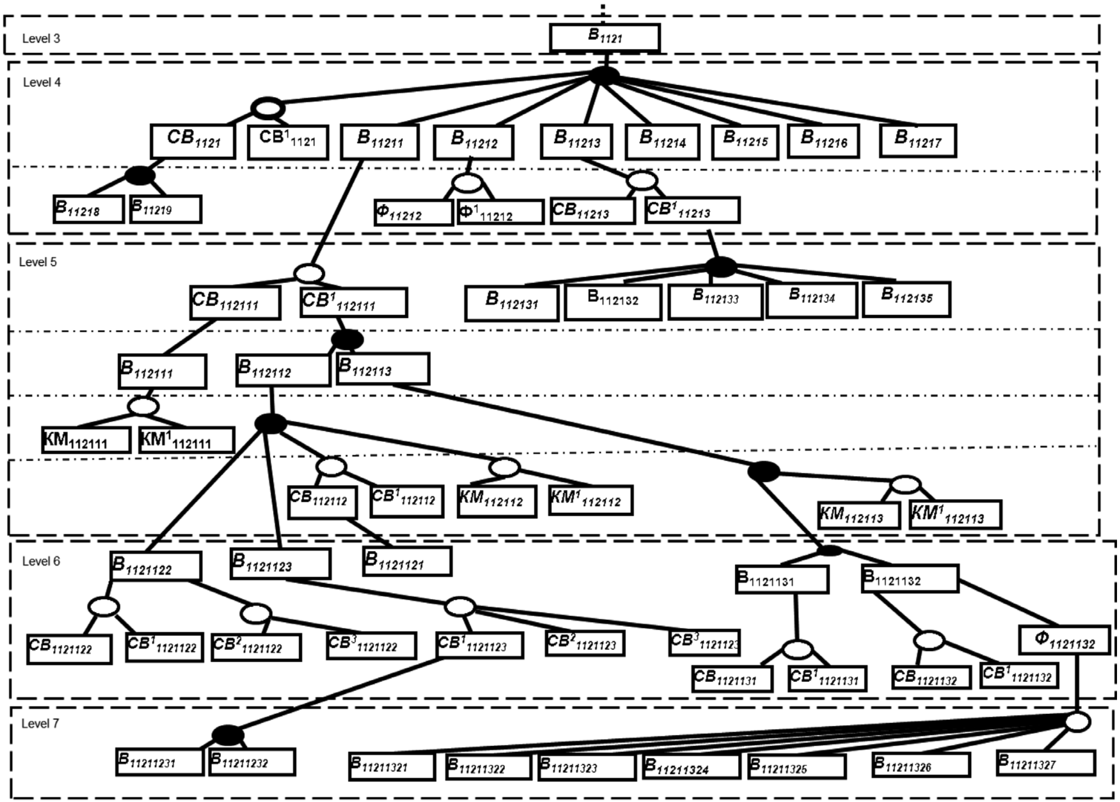


Figure 5.1. AND-OR Tree for the Center Sill Design of the General Purpose Open Wagon

described in Figure 4.3. The rivets ($B_{1121121}$) are respectively considered to be used for rivet connection (CB_{112112}) at level 6. Eventually, level 6 points to the following components of the top sill: I-iron ($B_{1121122}$) and brackets ($B_{1121123}$). The engineering solution for the I-iron is also proposed to be chosen as the variant from 36-40, table 5.1, while the variants of 42-44 in the same table are for the brackets. In case of the search for the bracket design solution ($CB^{1}_{1121123}$), there are provided the elements $B_{1121131}$, and $B_{1121132}$ at level 6.

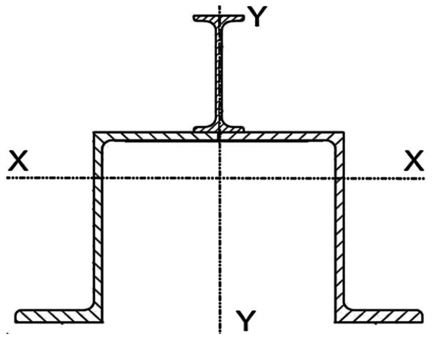
Table 5.1

Components of AND-OR Tree.
General-Purpose Open Wagon Center Sill Design

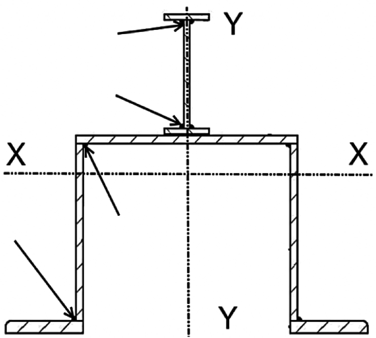
Item No.	Schematic symbol	Element description
1	B_{1121}	Center sill
2	CB_{1121}	Rivet connection
3	B_{11218}	Rivet 16*45
4	B_{11219}	Rivet 22*60
5	CB^{1}_{1121}	Welded joint
6	B_{11211}	Beam
7	B_{11212}	Binding course
8	$Ф_{11212}$	With hole
9	$Ф^{1}_{11212}$	Without hole
10	B_{11213}	Center plate
11	CB_{11213}	Casting
12	CB^{1}_{11213}	Assembly-welding
13	B_{112131}	Base
14	B_{112132}	Binding course
15	B_{112133}	Lateral rib
16	B_{112134}	Stiffening rib
17	B_{112135}	Horizontal rib
18	B_{11214}	Strip
19	B_{11215}	Front support
20	B_{11216}	Rear support
21	B_{11217}	Anti-wearing strip
22	CB_{112111}	Solid cross-section rolled beam
23	CB^{1}_{112111}	Assembly-welding
24	B_{112111}	Solid rolled beam
25	KM_{112111}	Steel of 09Г2С grade or 09Г2Д grade, 295 quality class
26	KM^{1}_{112111}	Steel of 10ХНДП grade, 345 quality class

Item No.	Schematic symbol	Element description
27	B_{112112}	Top sill
28	KM_{112112}	Steel of 09Г2С grade or 09Г2Д grade, 295 quality class
29	KM^{1}_{112112}	Steel of 10 ХНДП grade, 345 quality class
30	B_{112113}	Bottom sill
32	KM_{112113}	Steel of 09Г2С grade or 09Г2Д grade, 295 quality class
32	$KM_{1112113}$	Steel of 10ХНДП grade, 345 quality class
33	CB_{112112}	Rivet connection
24	$CB_{1112112}$	Welded joint
35	$B_{1121121}$	Rivet 16*60.02
36	$B_{1121122}$	I-bar
37	$CB_{1121122}$	Solid along the length
38	$CB_{11121122}$	Solid along the length
39	$CB_{21121122}$	Solid rolled
40	$CB_{31121122}$	Assembly-welding
41	$B_{1121123}$	Bracket
42	$CB_{1121123}$	Assembly-welding
43	$CB_{11121123}$	Casting
44	$CB_{21121123}$	Forging
45	$B_{11211231}$	Hinge
46	$B_{11211232}$	Rib
47	$B_{1121131}$	Hinge
48	$CB_{1121131}$	Casting
49	$CB_{111211232}$	Assembly-welding
50	$B_{1121132}$	Beam
51	$CB_{11211232}$	Solid along the length
52	$CB_{111211232}$	Solid along the length
53	$Ф_{1121132}$	Shape
54	$B_{11211321}$	2 Z – profiles
55	$B_{11211322}$	Solid omega-profile
56	$B_{11211323}$	2 channels and plate fishes
57	$B_{11211324}$	Rectangular pipe
58	$B_{11211325}$	Hexagonal hollow profile
59	$B_{11211326}$	D-pipe
60	$B_{11211327}$	Circular pipe

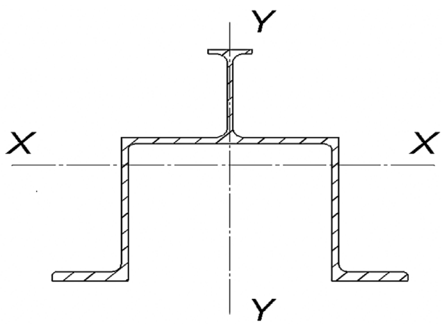
At level 6, the bottom sill (B_{112113}) has the hinge ($B_{1121131}$), which can be produced as variants 48-49 in table 4.1, the profile ($\mathrm{B}_{1121132}$) of variants 51 and 52, and various configurations ($\Phi_{1121132}$). The elements of the range $B_{11211321} - B_{11211327}$ (refer to table 5.1) are on final level 7 of AND-OR tree and can be named as the existing and perspective configurations of the bottom sill.



a) existing center sill made of top sill *(B_{112112})* and bottom sill *(B_{112113})*



b) perspective design, defined with AND-OR tree



c) perspective design, solid along the cross-section *(CB_{112111})*

Figure 5.2. The Existing and Perspective Designs of Center Sill for General-Purpose Open Wagon. Cross-sections

5.1.3. Examples How the Variants Description Can be Application for the Center Sill of General-Purpose Open Wagon

In order to check the performance of the developed AND-OR tree, we used it to display the contemporary typical structure of open wagon center sill in the form of AND tree (refer to figure 5.3). The basic elements of the structure are identified in figure 5.4 with structural and functional features, specified in table 5.1.

The analysis of the presented description of existing center sill design has proved the performance capabilities of the developed variants description and the possibility of its further application.

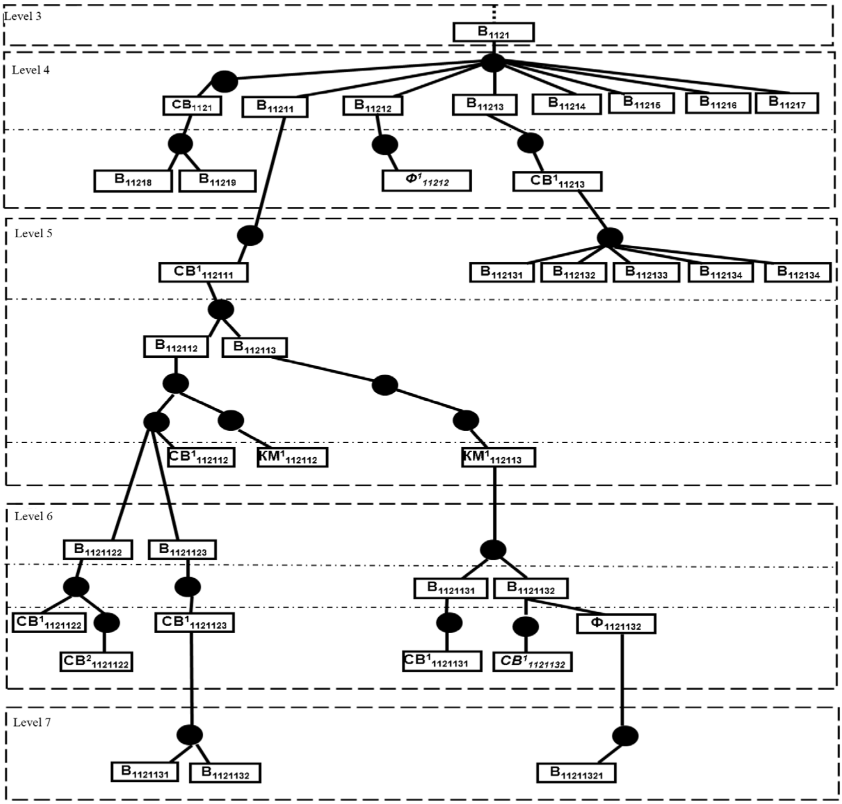


Figure 5.3. Structural AND Tree of the Center Sill Elements within the General-Purpose Open Wagon of Contemporary Typical Design

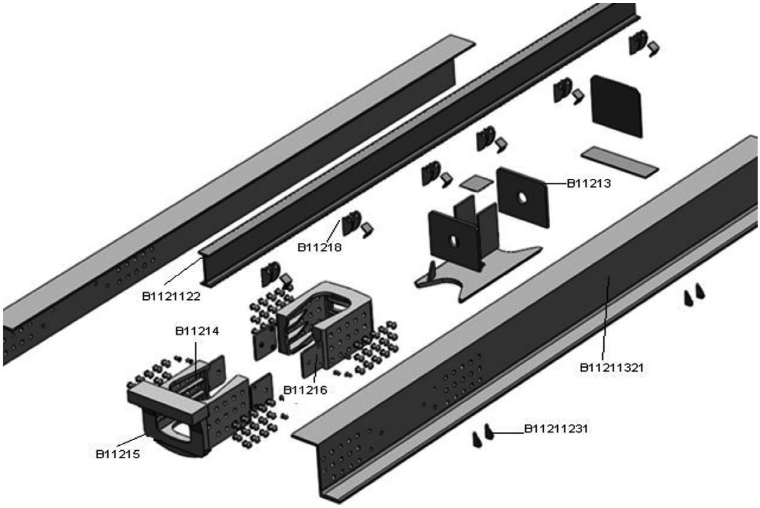


Figure 5.4. Contemporary Typical Design of the Center Sill of the General-Purpose Open Wagon. Elements Spread in the Space

One of the perspective directions to improve the effectiveness of the freight wagon is the improvement of its design by introduction of the profiles into its carrying system, which are able to ensure the reduction in general material consumption of the structures but provide the same strength and operational conditions as the previous structures. The results of the analysis on the perspective profiles for the wagon manufacture and the experience of other fields of machine-building have shown the reasonability to introduce the circular pipes into the supporting elements of the wagons.

The developed and reported in this paper AND-OR tree for the open wagon structure became the grounding for the further developments of AND tree for the open wagon center sill made of circular pipes. The information on it is submitted in the next chapter.

5.2. Structural and Functional Models for Freight Wagon Constructions

The current level of science and technology development requires to apply (often develop and apply) the innovative adaptive methods of scientific and engineering activity on the base of systematic approach both for the new generation body module or/and for those body modules that have been deeply and comprehensively modernized. The above said is explained by the fact that the common peculiarity of the existing methods of scientific and research work as well as of research and development work on the wagon body pursuing the objective to improve its performance is separate considerations of wagon units and parts. Therefore, the traditional approach does not allow us to consider the interaction between the wagon body elements at operation at the different stages of their service life, and consequently we cannot perform accurate analysis on the relevant basic elements of the component units. Moreover, the introduction of principles of systematic approach is expected to permit the open wagon to be presented in the form of the interrelated and interacting subsystems that are the aggregate of the components, singled out from the wagon structure. It is also expected to maximally take into account the main factors of their functioning, namely: the material properties of the main components (strength, corrosion resistances, weldability, plasticity, etc.), technological requirements (take into consideration the energy consumption and features of production and repair technology), operational conditions (take into account the features of open wagon body module operation) and design features (the features and the shape of the module/ components/ units/ elements). Furthermore, the change or degradation of wagon parameters at the operation stages (for example, defining the scope of repairs or whether to have the prolongation of operation period) are also to be regarded by the systematic approach.

Eventually, when making solution on the described above issue, the top-priority task is the development of structural and functional model for the wagon body, which is its description in terms of its basic elements or structure units, and the functional relations between them, that gives the opportunity to formalize or to expand the description of the functional characteristics of the body module within the general-purpose freight wagon and its relevant subsystems, as well as to apply creative and search methods for elements development. These methods, in their turn, are able to stipulate new patentable engineering solutions. However, the analysis on numerous scientific, technical, and reference literature, relevant to the profile of the issue under the study, has showed the absence of information that the similar works have been performed.

The solution for the mentioned complex scientific and engineering problem is preconditioned by the necessity to solve the range of tasks, among which may be identified the following: the development of the structural description, the function identification for the modules/components/basic elements of structure, the identification of the relevant special conditions and restrictions under which the functions are to be performed.

The objective of section number 5 is to present the proposed structural and functional description of the hypothetic body module of the general-purpose open wagon and the peculiarities of its design illustrated by the examples of its application.

5.2.1. Module- Hierarchical Description of the Body Design of the Contemporary Open Wagon

For developing the design of the open wagon body module, the works have been performed in three stages. *The first stage* includes the works over the formalized description of the open wagon body module. This type of description provides identification of three hierarchical levels for the open wagon design. Herein, the body module (B_{11}) is considered as the element of the first level, while its unit elements belong to the second level. The elements that conventionally are not subjected to the further division compose the basic elements of the third level. Taking into consideration the fact that at studying the existing as well as at developing the new open wagons, the body modules should be also considered as it is the bearing system, there emerges the necessity to refer to the development of the formalized description of this system structure with identification of four hierarchical levels, but not of three per the stages (see systemized materials in figure 5.5).

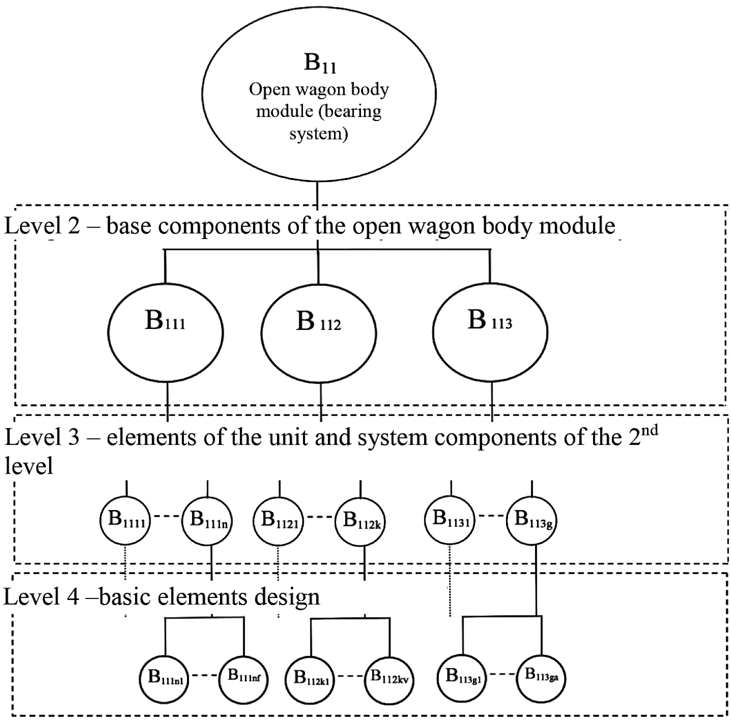


Figure 5.5. Module-Hierarchical Scheme of the Contemporary Open Wagon Body

In other words, we have introduced the additional or the second level, the elements of which are the base components of the body module (B_{11}): the component of wagon sides and ends (B_{111}), the frame component (B_{112}), the component of unloading facilities (B_{113}). The latter are divided into the relevant units at the next hierarchical level. Thus, as the units of open wagon sides and ends (B_{111}) are regarded as follows: wagon side B_{1111}, wagon end B_{1112}, connecting complex (enhancing complex the connections of sides and ends - B_{1113}). Within the components of the frame (B_{112}), we can distinguish the following: center sill (B_{1121}), centre bearer (B_{1122}), cross-bearer (B_{1123}) and head stock (B_{1124}). The components of the unloading facilities (B_{113}): manhole cover (B_{1131}); fitting and locking devices of manhole cover (B_{1132}), manhole cover lifting device (B_{1133}). In its turn, the principle decomposition elements of the third hierarchical level make up the fourth hierarchical level. There are more than 100 units of such elements of the fourth level within the open wagon body module, therefore (due to limits for the thesis research volume), they are not considered in details, but are only partially analyzed in the case of the consideration.

5.2.2. Functions of the Components Body within the Contemporary Open Wagon

At the second stage we defined the functions (F) of each subsystem. For this purpose, it is reasonable to apply the following description:

$$F = (D,\ G,\ H)\,, \tag{5.1}$$

where D is an action, performed by the open wagon body module (or by its subsystem component), that lead to the desired result;

G is an object, to which action D is directed;

H is special conditions and restrictions of action D.

When developing the structural-functional model, it is reasonable to apply the principles of modularity and hierarchy. In accordance with them, the primarily defined the main functions of the open wagon are those that belong to the unit of the top or zero level of the hierarchical structure. Upon identification of the main functions of the open wagon, we define the main useful functions and additional related functions of the modules (the first hierarchical level) that are able to ensure the performance of the main functions. Moreover, each element of the first hierarchical level is considered as individual engineering system. This allows us to identify the structural elements of level 2 and their useful and additional related functions, which provide level 1 elements functioning. Similarly, we have carried out the decomposition into the functional elements at the third and at the fourth hierarchical levels. The restrictions were considered in accordance with the level hierarchy, i.e. the restrictions for general structure set the requirements for component modules that, in their turn, conditions the restrictions for the components, while the restrictions of the units of the forth level make up the requirements for the basic elements. In general, as the main restrictions may be identified as the following: weight requirements, geometrical/ space/ shape restrictions, restrictions on energy consumption, restrictions of technological nature, unification in repairs and production, surface processing, etc.

A*t the concluding third* stage we construct the module-hierarchical model of the open wagon body module functional interaction between its components.

5.2.3. Structural-Functional Model of the Contemporary Hypothetical General-Purpose Open Wagon Body

For the described above procedure the following signs have been chosen: the open wagon is denoted by level-position index of B_0. The special conditions and restriction for the open wagon actions are marked as H_{0i} (where *i* varies depending on the quantity of relevant restrictions for the open wagon/ module/ component/ unit/ basic element). F_0 stands for the open wagon functions.

Level 1 contains the main modules of the open wagon structure that are denoted by B_{1x} indices, for which $\mathbf{x} \in [1;4]$. The special conditions and restrictions for the actions of level 1 modules are written as H_{1xi}, while their functions are F_{1x}.

Level 2 includes the components of level 1 module and they are marked by level-position indices of B_{1xn} (*n* varies depending on the quantity of the components in the composition of the relevant module). For open wagon body module is said $\mathbf{n} \in [1;3]$. The special conditions and restriction of the actions of level 2 modules are denoted as H_{1xni}, their functions - as F_{1xn}.

Level 3 embraces the components of level 2 modules and their symbols are the level-position indices of B_{1xnl} (*l* varies depending on the quantity of the components in the composition of the relevant constituent). The special conditions and restrictions of the actions for the units are expressed by H_{1xnli}., while their functions are respectively F_{1xnl}.

Level 4 contains the basic elements of level 3 units denoted by the level-position indices of B_{1xnlm} (*m* varies depending on the quantity of the basic elements in the composition of the relevant unit). The special conditions and restrictions of the basic elements actions are denoted by H_{1xnlmi} with their functions as F_{1xnlm}.

The modules/components/units/basic elements within the open wagon structure generally perform several functions (k>1). In these cases, the functions are denoted for the first, second, third and fourth levels through: $F^{1}_{1x}...F^{k}_{1x}$; $F^{1}_{1xn}...F^{k}_{1xn}$; $F^{1}_{1xnl}...F^{k}_{1xnl}$ and $F^{1}_{1xnlm}...F^{k}_{1xnlm}$, where k varies depending on the number of the component functions.

The summarized results of the function analysis for the hypothetical general-purpose open wagon with detailed body elaboration per the units are shown in Table 5.2. Due to the fact that the open wagon is a solid supporting structure, under interaction (see column 3 of table 5.2), we assume the work unser various kinds of loading.

The information, provided in table 4.2, permitted us to develop the structural-functional model of the open wagon body module in the form of the relevant chart

Table 5.2

Analysis of the Functions for Hypothetical General-Purpose Open Wagon with the Body Module Detailed Elaboration

Item No.	Unit: the object of the directed action of the open wagon/ module/ component/ unit	Functions of the open wagon/ module/ component/ unit. The special conditions and restrictions (*H*)
1	2	3
1	B_0– general-purpose open wagon: G_1 – railway track; G_2 – cargo; G_3– other cars or locomotive.	$F^{1}_{0}...F^{3}_{0}$ – cargo transportation on condition of the relevant level of engineering and economic operational parameters; if the requirements of $H_{01}...H_{0i}$ specified in [12-17, 19, 22, 24] are met.
2	B_{11}– body module: G_2; B_{12}; B_{13}; B_{14}.	F^{1}_{11} – cargo placement; F^{2}_{11} – cargo preservation during transportation; F^{3}_{11} –unloading under gravity forces; F^{4}_{11} – interaction (including accommodation and transfer of the loads) with modules B_{12}, B_{13} (including their placement) and B_{14}, if the requirements of $H_{111}...H_{11i}$ specified in [12-17, 19, 22, 24] are met.
3 4	B_{12}– automatic coupling module: G_3; B_{11}.	F^{1}_{12}– wagon coupling with another wagon or the locomotive, as well as absorption of forces, transferred from the other wagon or the locomotive; F^{2}_{12}– interaction with module of B_{11}, on condition that the requirements $H_{121}...H_{12i}$ provided by [12-17, 19, 22, 24] are met.
5	B_{13} – brakes equipment module: B_{14}; B_{11}.	F^{1}_{13} – development of the resistance to motion at braking, wagon keeping stastic (interaction with module B_{14}); F^{2}_{13}– interaction with module B_{11}, if the requirements of $H_{131}...H_{13i}$ specified in [12-17, 19, 22, 24] are met.

Item No.	Unit: the object of the directed action of the open wagon/ module/ component/ unit	Functions of the open wagon/ module/ component/ unit. The special conditions and restrictions (*H*)
1	2	3
6	B_{14} – module of undercarriage structure: G_1; B_{11}; B_{13}.	F^1_{14} – ensuring the required characteristics of open wagon movement on the rails; F^2_{14} – interaction with module B_{11}; F^3_{14} – interaction with module B_{13} if the requirements of $H_{141}...H_{14i}$ specified in [12-17, 19, 22, 24] are met.
7	B_{111} – the components of sides and ends: G_2; B_{112}; B_{113}.	$F^1_{111}=F^1_{11}$; $F^2_{111}=F^2_{11}$; F^3_{111} – interaction with B_{112}; F^4_{111} – interaction with B_{113}, if the requirements of $H_{1111}\ldots H_{111i}$ are met.
8	B_{112} – frame components: G_2; B_{12}; B_{13}; B_{14}; B_{111}; B_{113}.	$F^1_{112}=F^1_{11}$; $F^2_{112}=F^2_{11}$; F^3_{112} – placement and interaction with B_{12}; F^4_{112} – placement and interaction with B_{13}; F^5_{112} – interaction with B_{14}; F^6_{112} – interaction with B_{111}; F^7_{112} – interaction with B_{113}, if the requirements of $H_{1121}\ldots H_{112i}$ are met
9	B_{113} – the components unloading facilities: G_2; B_{111}; B_{112}.	$F^1_{113}=F^1_{11}$; $F^2_{113}=F^2_{11}$; $F^3_{113}=F^3_{11}$; F^4_{113} – interaction with B_{111}; F^5_{113} – interaction with B_{112}, if the requirements of $H_{1131}\ldots H_{113i}$ are met.
10	B_{1111} – wagon side: G_2; B_{1112}; B_{1113}; B_{1122}, B_{1123}, B_{1124} B_{1132}.	$F^1_{1111}=F^1_{11}$; $F^2_{1111}=F^2_{11}$; F^3_{1111} – interaction with B_{1112} and B_{1113}; F^4_{1111} – interaction with B_{1122}, B_{1123}, B_{1124}; F^5_{1111} – interaction with B_{1132}, if the requirements of $H_{11111}\ldots H_{1111i}$ are met.
11	B_{1112} – wagon ends: G_2; B_{1111}; B_{1113}; B_{1124}.	$F^1_{1112}=F^1_{11}$; $F^2_{1112}=F^2_{11}$; F^3_{1112} – interaction with B_{1111} and B_{1113}; F^4_{1112} – interaction with B_{1124}, if the requirements of $H_{11121}\ldots H_{1112i}$ are met.
12	B_{1113} – connection complex (sides and ends connection and strengthening complex): B_{1111}; B_{1112}.	F_{1113} – connection and interaction with B_{1111} and B_{1112}, if the requirements of $H_{11131}\ldots H_{1113i}$ are met.
13	B_{1121} – center sill: B_{1122}; B_{1123}; B_{1124}; B_{12}; B_{1132}; B_{1133}; B_{12}.	F^1_{1121} – placement and interaction with: B_{1122}, B_{1123}, B_{1124}; $F^2_{1121}=F^3_{112}$; F^3_{1121} – interaction with B_{1132}; F^4_{1121} – interaction with B_{1133}; $F^5_{1121}=F^4_{112}$, if the requirements of $H_{111}\ldots H_{11i}$ are met.
14	B_{1122} – centre bearer: B_{1121}; B_{1111}; B_{1131}.	F^1_{1122} – interaction with B_{1121}; F^2_{1122} – interaction with B_{1111}; F^3_{1122} – interaction at cargo unloading with B_{1131}, if the requirements of $H_{11221}\ldots H_{1122i}$ are met.

Item No.	Unit: the object of the directed action of the open wagon/ module/ component/ unit	Functions of the open wagon/ module/ component/ unit. The special conditions and restrictions (*H*)
1	2	3
15	B_{1123} – cross-bearer: B_{1121}; B_{1111}; B_{14};B_{1131}.	F^1_{1123}– interaction with B_{1121}; F^2_{1123}– interaction with B_{1111}; $F^3_{1123}=F^5_{112}$; F^4_{1123}– interaction at cargo unloading with B_{1131}, if the requirements of $H_{11231}\ldots H_{1123i}$ are met.
16	B_{1124} – head stock: B_{1121}; B_{1112}; B_{1111}; B_{12}; B_{1131}.	F^1_{1124}– interaction with B_{1121}; F^2_{1124}– interaction with B_{1112}; F^3_{1124}– interaction with B_{1111}; F^4_{1124} – placement of B_{12} elements; F^5_{1124}– interaction at cargo unloading with B_{1131}, if the requirements of $H_{11241}\ldots H_{1124i}$ are met.
17	B_{1131} – manhole cover: G_2; B_{1122}; B_{1123}; B_{1124}; B_{1132}; B_{1133};	$F^1_{1131}= F^2_{11}$; $F^2_{1131}= F^3_{11}$; F^3_{1131}– interaction with B_{1132}; F^4_{1131}– interaction at cargo unloading with B_{1133}; F^5_{1131}– interaction with: B_{1122}, B_{1123}, B_{1124}, if the requirements of $H_{11311}\ldots H_{1131i}$ are met.
18	B_{1132} – fitting and locking devices of manhole cover: B_{1131}; B_{1121}; B_{1111}.	F^1_{1132}– interaction with B_{1131}; F^2_{1132}– interaction with B_{1121}; F^3_{1132}– interaction with B_{1111}, if the requirements of $H_{11321}\ldots H_{1132i}$ are met.
	B_{1133} – manhole cover lifting device: B_{1131}; B_{1121}.	F^1_{1133}– interaction with B_{1131}; F^2_{1133}– interaction with B_{1121}, if the requirements of $H_{11331}\ldots H_{1133i}$ are met.

(refer to figure 4.7), where the chart apices represent the modules/ components/ units of the structure and the ribs in the chart stand for structural and functional relations between them. Compared with the flow chart, this one is more compact that is essential for description of a complex object and more demonstrable as compared with matrix or table description.

The apices in figure 5.6 chart symbolize the open wagon, the distinguished structure modules, the components of the open wagon body module and their units and the objects (G_1, G_2, G_3), at which the open wagon actions are directed. The structural relations between the elements are shown in the firm lines, while the functions of the elements are the dash lines. They come out of the apices of those elements that perform relevant functions, and come into the other apices of the elements, at which such function is directed. The explanation of the symbols of the apices-elements, apices-objects and ribs in the chart are described in table 5.2.

In figure 4.6 one can see that the open wagon interacts with, or accompanied by the related response, influences the railway track (G_1), the cargo (G_2) and the other wagons or the locomotive (G_3). Furthermore, the main functions of the open wagon are shared between the components of the first hierarchical level,

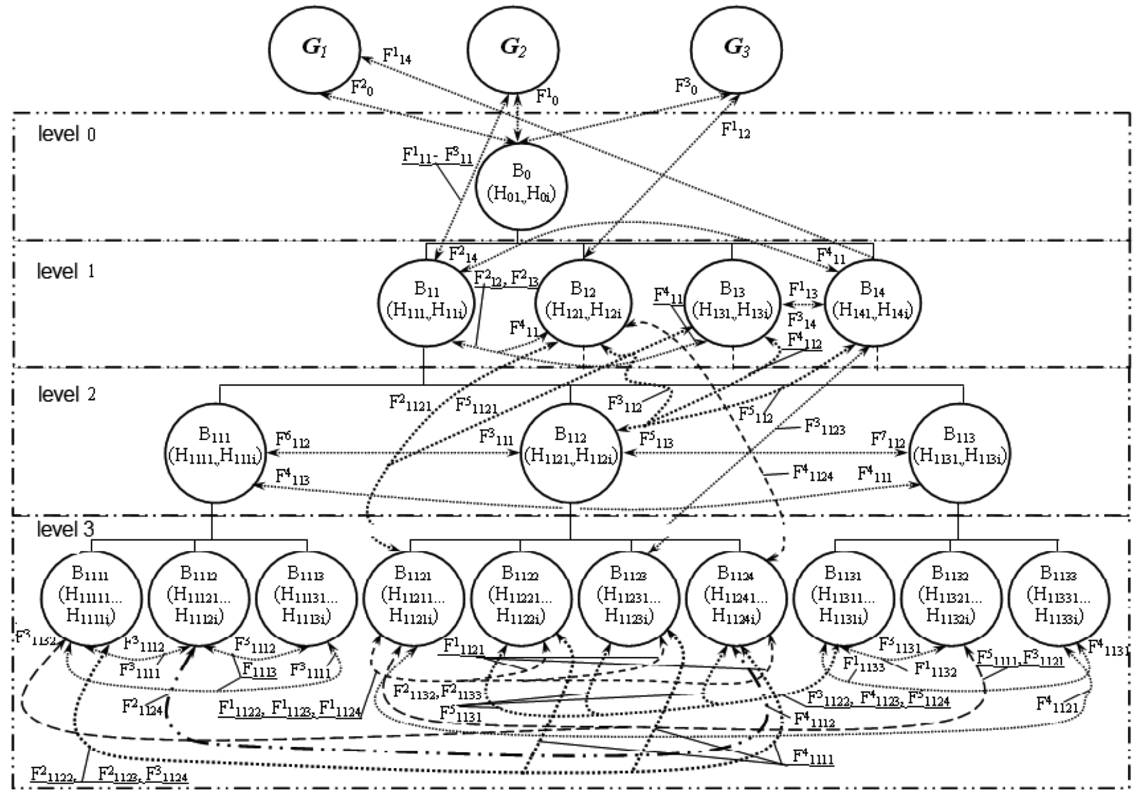


Figure 5.6. Structural-Functional Model of the Body Module of the Hypothetical General-Purpose Open Wagon

in particular between the modules. Thus, the open wagon body module (B_{11}) directly interacts with G_2 (functions $F^1{}_{11}$, $F^2{}_{11}$, $F^3{}_{11}$) and in addition performs the function of $F^4{}_{11}$ with modules B_{12}, B_{13} and B_{14}, if the requirements of H_{111}… H_{11i} are met. B_{12} module carries out $F^1{}_{12}$ function with G_3, and $F^2{}_{12}$ function with B_{11} module, taking into account the requirements of H_{121}...H_{12i}. B_{13} module performs function $F^1{}_{13}$ with B_{14} module while $F^2{}_{13}$ function is done with B_{11} module when the conditions of H_{131}…H_{13i}. B_{14} module incorporates G_1 for $F^1{}_{12}$ function and B_{11} module for $F^2{}_{12}$ function, taking into account the requirements of H_{121}... H_{12i}. Eventually, the conclusion may be made for the modules of the contemporary open wagon structure: the brakes equipment module does not directly interacts with the objects (G_1, G_2, G_3), and its main actions are directed at B_{14} module.

If we consider the functions of the body module components at the second hierarchical level, the chart tells us that all the body module components (B_{111}, B_{112}, B_{113}) interact with each other. Herein, the main functions of the body module in terms of interaction with the other modules (B_{12}, B_{13}, B_{14}) are performed by the frame component of B_{112} ($F^3{}_{112}$, $F^4{}_{111}$, $F^5{}_{112}$).

Analyzing the third hierarchical level of the structural-functional chart, we would like to comment on it. The units (B_{1111}, B_{1112}, B_{1113}) of the side and end component (B_{111}) interact between each other. Herein, the wagon side (B_{1111}) also interacts ($F^4{}_{1111}$) with units of B_{1122}, B_{1123}, B_{1124}, while the wagon end (B_{1112}) interacts with ($F^4{}_{1112}$) head stock. (B_{1124}). B_{1121} unit (center sill) places and respectively interacts with the other units (B_{1122}, B_{1123}, B_{1124}) of the frame component (B_{112}). It also performs functions of placing auto-coupling facility elements ($F^2{}_{1121}$=$F^3{}_{112}$) and brakes equipment module ($F^5{}_{1121}$= $F^4{}_{112}$). This fact makes it the main supporting unit of the open wagon (B_0) provided that the work on the load bearing obtained from the undercarriage module (B_{14}) through the centre unit of B_{1123} is considered. Therefore, the operational suitability of whole structure directly depends on its technical state. The centre-bearer (B_{1122}), cross- bearer (B_{1123}) and head stock (B_{1124}) are arranged on the center sill (B_{1121}) and interact with wagon side (B_{1111}) when closed manhole covers, but when unloading they interact with the manhole cover (B_{1131}). This suggests that there exists a considerable number of the similar functions. In addition, through the basic elements of the cross- bearer (B_{1123}) participate in the body module support when it relies on the elements of undercarriage module (B_{14}). The head stock (B_{1124}) interacts with the wagon end (B_{1112}). The unit elements (B_{1131}, B_{1132}, B_{1133}) of the unloading facility component (B_{113}) have the functional relations between each other in addition to those with B_{1132} and B_{1133}. Moreover, B_{1131} interacts at unloading with B_{1122}, B_{1123}, and B_{1124}, but it performs the function of the floor ($F^1{}_{1131}$= $F^2{}_{11}$, $F^2{}_{1131}$= $F^3{}_{11}$) at transportation or storage of the cargo (G_2). The manhole cover fitting and locking devices (B_{1132}) also interact with B_{1121} and B_{1111}, while and the manhole cover lifting device (B_{1133}) does with B_{1121}.

Due to the limitation on the thesis research volume, we propose that the structural-functional model for the wagon side (B_{1112}) of 12-9745 open wagons by a Ukrainian manufacturer be used as the example for consideration on the structural-functional model for the body module basic elements. The model accounts 17 basic elements (refer to table 4.3, 2-nd column). In addition, table 4.3 pays attention to the functions of the basic elements of the wagon side and special conditions and restrictions (*H*).

Based on the materials submitted in table 5.3, matrix description of internal level functional connections between the basic elements of the wagon side (B_{1112}) has been developed for the above mentioned wagon model, as follows:

$$F^{B_{1112}} = \begin{pmatrix} (B_{11121}, B_{11121}) & (B_{11121}, B_{11122}) & \dots (B_{11121}, B_{111217}) \\ (B_{11122}, B_{11121}) & (B_{11122}, B_{11122}) & \dots (B_{11122}, B_{111217}) \\ \dots & \dots \quad \dots & \dots \\ (B_{111217}, B_{11121}) & (B_{111217}, B_{11122}) & \dots (B_{111217}, B_{111217}) \end{pmatrix} \quad (5.2)$$

where $(B_{11121}, B_{11121})=f^{B}_{1\text{-}1}$, $(B_{11121}, B_{11122})=f^{B}_{1\text{-}2}$, $(B_{11121}, B_{111217})=f^{B}_{1\text{-}17}$, etc. are functional connections between the basic elements B_{11121} and B_{11121}, B_{11121} and B_{11122}, B_{11121} and B_{111217}, etc.

Table 5.3

Analysis on Functions of the Basic elements of the Wagon Side within the Body Module of the General-Purpose Open Wagons (12-9745 Model)

Item No.	Basic element: the object of the directed action	Functions of the basic elements. The special conditions and restrictions (*H*)
1	B_{11121} – top cord: B_{1121}; B_{11127}; B_{111213}; B_{11123}; B_{111211}; B_{11129}; B_{111212}.	F^{1}_{11121}– interaction with B_{1121}; F^{2}_{11121}– interaction with B_{11127}; F^{3}_{11121}– interaction with B_{111213}; F^{4}_{11121}– interaction with B_{11123}; F^{5}_{11121}– interaction with B_{111211}; F^{6}_{11121}– interaction with B_{11129}; F^{7}_{11121}– interaction with $B_{111212,}$ if the requirements of $H_{111}...H_{11r}$ are met.
2	B_{11122} – bottom cord: B_{1124}; B_{11128}; B_{11123}; B_{11124}; B_{111214}; B_{11129}	F^{1}_{11121}– interaction with B_{1124}; F^{2}_{11121}– interaction with B_{11128}; F^{3}_{11121}– interaction with B_{11123}; F^{4}_{11121}– interaction with B_{11124}; F^{5}_{11121}– interaction with B_{111214}; F^{6}_{11121}– interaction with B_{11129}, if the requirements of $H_{111}...H_{11r}$ are met.
3	B_{11123} – side stake: B_{11121}; B_{11125}; B_{11126}; B_{11122}; B_{1111}; B_{11127}; B_{11128}; B_{1124}.	F^{1}_{11123}– interaction with B_{11121}; F^{2}_{11123}– interaction with B_{11125}; F^{3}_{11123}– interaction with B_{11126}; F^{4}_{11123}– interaction with B_{11122}; F^{5}_{11123}– interaction with B_{1111}; F^{6}_{11123}– interaction with B_{11127}; F^{7}_{11123}– interaction with B_{11128}; F^{8}_{11123}– interaction with B_{1124}, if the requirements of $H_{111}...H_{11r}$ are met.

Item No.	Basic element: the object of the directed action	Functions of the basic elements. The special conditions and restrictions (H)
4	B_{11124} – vertical stake: B_{11126}; B_{11122}; B_{11128}; B_{1124}; B_{111210}.	F^1_{11124} – interaction with B_{11126}; F^2_{11124} – interaction with B_{11122}; F^3_{11124} – interaction with B_{11128}; F^4_{11124} – interaction with B_{1124}; F^5_{11124} – interaction with B_{111210}, if the requirements of $H_{111}...H_{11r}$ are met.
5	B_{11125} – horizontal top chord: B_{11123}; B_{11127}; B_{11129}.	F^1_{11125} – interaction with B_{11123}; F^2_{11125} – interaction with B_{11127}; F^3_{11125} – interaction with B_{11129}, if the requirements of $H_{111}...H_{11r}$ are met.
6	B_{11126} – horizontal bottom chord: B_{11123}; B_{11124}; B_{11127}; B_{11128}; B_{11129}.	F^1_{11126} – interaction with B_{11123}; F^2_{11126} – interaction with B_{11124}; F^3_{11126} – interaction with B_{11127}; F^4_{11126} – interaction with B_{11128}; F^5_{11126} – interaction with B_{11129}, if the requirements of $H_{111}...H_{11r}$ are met.
7	B_{11127} – top plate of lining: G_2; B_{11121}; B_{11123}; B_{11125}; B_{11126}; B_{111215}; B_{111217}; B_{111213}.	F^1_{11127} – interaction with B_{11121}; F^2_{11127} – interaction with B_{11123}; F^3_{11127} – interaction with B_{11125}; F^4_{11127} – interaction with B_{11126}; F^5_{11127} – interaction with B_{111215}; F^6_{11127} – interaction with B_{111217}; F^7_{11127} – interaction with B_{111213}, if the requirements of $H_{111}...H_{11r}$ are met.
8	B_{11128} – bottom plate of lining: G_2; B_{11126}; B_{11122}; B_{11123}; B_{11124}; B_{111215}; B_{111217}.	F^1_{11128} – interaction with B_{11126}; F^2_{11128} – interaction with B_{11122}; F^3_{11128} – interaction with B_{11123}; F^4_{11128} – interaction with B_{11124}; F^5_{11128} – interaction with B_{111215}; F^6_{11128} – interaction with B_{111217}, if the requirements of $H_{111}...H_{11r}$ are met.
9	B_{11129} – staircase: B_{11121}; B_{11122}; B_{11125}; B_{11126}.	F^1_{11129} – interaction with B_{11121}; F^2_{11129} – interaction with B_{11122}; F^3_{11129} – interaction with B_{11125}; F^4_{11129} – interaction with B_{11126}, if the requirements of $H_{111}...H_{11r}$ are met.
10	B_{111210} – strip: B_{11124}; B_{1124}.	F^1_{111210} – interaction with B_{11124}; F^2_{111210} – interaction with B_{1124}, if the requirements of $H_{111}...H_{11r}$ are met.
11	B_{111211} – bracket: B_{11121}; B_{111212}.	F^1_{111211} – interaction with B_{11121}; F^2_{111211} – interaction with B_{111212}, if the requirements of $H_{111}...H_{11r}$ are met.
12	B_{111212} – clamp: G_2; B_{111211}; B_{11121}.	F^1_{111212} – interaction with $B_{111211;}$ F^1_{111212} – interaction with B_{11121}, if the requirements of $H_{111}...H_{11r}$ are met.
13	B_{111213} – rib: B_{11121}; B_{11127};	F^1_{111213} – interaction with B_{11121}; F^2_{111213} – interaction with B_{11127}, if the requirements of $H_{111}...H_{11r}$. are met.
14	B_{111214} – tie down ring: G_2; B_{11122}.	F_{111214} – interaction with B_{11122}, if the requirements of $H_{111}...H_{11r}$ are met.
15	B_{111215} – angle fitting: B_{11127}; B_{11128}; B_{111216}.	F^1_{111215} – interaction with B_{11127}; F^2_{111215} – interaction with B_{11128}; F^3_{111215} – interaction with B_{111216}; if the requirements of $H_{111}...H_{11r}$ are met.
16	B_{111216} – internal stair: B_{111215}; B_{11127}; B_{11128}.	F^1_{111216} – interaction with B_{111215}; F^2_{111216} – interaction with B_{11127}; F^3_{111216} – interaction with B_{11128}, if the requirements of $H_{111}...H_{11r}$ are met.

Item No.	Basic element: the object of the directed action	Functions of the basic elements. The special conditions and restrictions (H)
17	B_{111217} – tie down devices: G_2; B_{11127}; B_{11128}.	F^1_{111217}– interaction with B_{11127}; F^2_{111217}– interaction with B_{11128}, if the requirements of $H_{111}...H_{11r}$ are met.

The conditions to form the elements, for example (B_{11121}, B_{11121}), (B_{11121}, B_{11122}), etc., of matrix $F^{B_{1112}}$ are to be defined through the following logical expression: $f^B_{1\text{-}1}=1$, if between elements of (B_{11121}, B_{11121}) there exist functional direct connections or $f^B_{1\text{-}1}=0$ otherwise. Thus, for example, between the basic elements of the wagon end and the body module (12-9745) there is functional connection between top cord (B_{11121}) and side stake (B_{11123}) and therefore $f^B_{1\text{-}3}=1$.

Taking into account the above said, the internal level functional connections of the basic elements of the wagon side (B_{1112}) of the body module (12-9745 model) may be expressed in the forms of the matrix (refer to table 5.4).

Table 5.4

Adjacency Matrix of Internal Level Functional Connections of the Basic Elements of the Wagon End (B_{1112}). Model 12-9745 Open Wagons

	B_{11121}	B_{11122}	B_{11123}	B_{11124}	B_{11125}	B_{11126}	B_{11127}	B_{11128}	B_{11129}	B_{111210}	B_{111211}	B_{111212}	B_{111213}	B_{111214}	B_{111215}	B_{111216}	B_{111217}
B_{11121}	0	0	1	0	0	0	1	0	1	0	1	1	1	0	0	0	0
B_{11122}	0	0	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0
B_{11123}	1	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
B_{11124}	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
B_{11125}	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0
B_{11126}	0	0	1	1	0	0	1	1	1	0	0	0	0	0	0	0	0
B_{11127}	1	0	1	0	1	1	0	0	0	0	0	0	1	0	1	0	1
B_{11128}	0	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0	1
B_{11129}	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
B_{111210}	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
B_{111211}	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
B_{111212}	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
B_{111213}	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
B_{111214}	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B_{111215}	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0
B_{111216}	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0
B_{111217}	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0

This adjacency matrix may be used for studying interrelations of the relevant apices; and in general case – as mathematical model for solving design-engineering problems of new units development for open wagons on the base of contemporary methodology of design for its studying at PC with the objective to obtain the required data for the supporting systems of open wagons (characteristics of their functioning, flow of operational and dynamic processes, expected technical and economic indices, etc.).

The results of the analysis of the presented above structural-functional model for the open wagon body module have been applied for development open wagons of 12-9904 model and 12-9904-0 model made by PJSC DMZ. The new procedure allowed the manufacturer to reduce production costs at the account of electricity and natural gas saving, and to refuse from the complex equipment for drilling, piercing, riveting as well as the tools and accessory for open wagon production and repair.

5.3. Functional Cost Analysis for Freight Wagon Carrying Systems

The important constituent of the scientific and research activities as well as of the research and development work aiming at the development of new generation freight wagons is economically oriented design of their structures and components. At present, for the design and research of the freight wagons structures, directed at reduction in their prime cost, the conventional substantive approach is applied, where the engineer or the researcher is looking for the ways to reduce the expenditures in a particular case of the design. However, the world's leading experience of engineering systems development has proved the reasonability to apply in such cases the functional approach, which makes up the base for functional-cost analysis. The approach foresees the analysis on the abstract functions of the engineering systems. That means that the real manufacture of the engineering system structure is not taken into account but they study if it is necessary to perform the certain functions of the systems with their quantitative characteristics, and define the ways to reduce the costs. The application of the functional-cost analysis (Activity Based Costing, ABS) for the system study within the freight wagons and their components is able to create the opportunity of the scientifically justified balance between the prime cost and the usefulness.

The objective of this section is to show the peculiarities of the suggested procedure of functional-cost analysis for supporting structures of the freight wagons.

5.3.1. The Generalized Procedure of Functional-Cost Analysis of the Freight Wagon Supporting Structures Performance

The functional-cost analysis is based on the assumption that the functions convert the resource into the product. Moreover, for the freight wagons the idle parts of their structure are the resource that is constantly transported or extra weight but not the useful element. The concept of the functional-cost analysis permits us to describe the efficiency of freight wagon supporting structures in financial or monetary terms. The mentioned takes place at the account of physical reflection of the certain components functions within the structure and of the level of resources utilization by the functions, as well as by studying the reasons why the resources are used. The results of the functional-cost analysis are the foundation for making the decisions in terms of modernization or rebuilding (both structural and functional) of the freight wagons supporting systems. The information, obtained with the help of the functional-cost analysis shows the possibilities of the resources redistribution with the maximal strategic benefit, identifies the opportunities of the key factors (strength and operational reliability indices) and defines optimal variants of resources investment. The main advantages of the functional-cost analysis applied for the freight wagons as compared with the concept analysis are the following: its systematic approach in case of identification of all the possible excessive expenditures (manpower, material and energy consumption, etc.) in the existing models or the models under development, its systematic application of the engineering creative methods when searching the new engineering solutions with the reduced costs, and clear vision of the processes of load accommodation and their influence on the prime cost. Thus, we are not limited here by only the direct costs or by the total product volume released.

The procedure of functional-cost analysis for the freight wagon supporting structures may be defined generally as the following main stages:

1) the development of the technical offer for the research;
2) identification and determination of the functions for the object elements;
3) identification of "odd" functions or useless ones, and the functions bearing the excessive costs by cost estimation for each functions performance (more often in the form of monetary equivalent or in the form of the material or the energy consumption, etc.);
4) elimination of the elements with odd functions and selection of the most reasonable engineering solutions for the elements with excessive costs;
5) practical implementation of the results of the functional-cost analysis.

The above mentioned action plan includes five interrelated stages, each composed of several separate stages. Herein, the sequence, provided by the action plan, is mandatory. More widely the action plan may be characterized by the following activities:

1) preliminary stage, the research object and the objectives are selected (total supporting construction or its certain part); technical offer is being developed;

2) information and analytical stage, when they collect the information the engineering solutions, the costs, the operation conditions and the drawbacks of the object. Further, they define the functions of the components and the conditions of their performance. The next important stage is the construction of the object structural-functional model (refer to the previous section);

3) the activities of the third stage are devoted to analysis and classification of the identified formalized function model. The described element functions may de divided into four groups: main, basic, additional and odd. Thus, the main functions are performed by the basic elements and refer to the elements that directly ensure the operation of the basic elements. It should be noted that if exclusion of one of the main functions, the whole set of the main functions cannot be performed. The additional functions are related to the elements that optimize implementation of the main functions or the basic ones, making it more effective, acceptable or attractive for the consumer. In case of elimination of any additional function the object remains in operation, however, the indices of quality are reduced. The odd functions refer to the elements that do not play any essential roles or have no role at all in providing the object performance or in improving its quality. Therefore, if the exclusion of an odd function and its related elements, the indices of quality do not reduce and even improve in some cases.

Eventually, the function costs should be defined and compared. We regard two main methods of function cost identification: more accurate direct calculation and approximate method of experts' comparisons. The first method is based on identification of a function cost as calculation of the production cost (includes costs for the main and additional materials, manpower, energy consumption, factory overhead costs). The second method is based on relative subjective estimation with the development of the data tables for the assessed elements. The latter are accrued the scores and their analysis brings the conclusions about the usefulness or the relevant cost of the elements.

5.3.2. Determination of Production Primary Cost of the Freight Wagon Element Functions on the Base of Structural-Functional Model

Production prime cost of the elements functions of the studied object (freight wagon or one of its components) is suggested to be determined on the base of the structural-functional model that may be written as the following mathematical dependencies, arranged in ascending order hierarchy:

$$C_{ijlkm} = C_{ijlkm}^{main.mat.} + C_{ijlkm}^{add.mat.} + C_{ijlkm}^{Man} + C_{ijlkm}^{E} + C_{ijlk}^{indir.}; \qquad (5.3)$$

where C_{ijlkm} –the prime cost of *m* basic element (*i, j, l, k, m* – level-position indices, corresponding to the codes of the studied component of the module-hierarchical chart: *i* – corresponds to the item number of the studied wagon variant; *j* – corresponds to the number of the formalized description module, which includes the studied component; *l* – corresponds to the item number of the formalized description, which includes the studied element; *k* – corresponds to the item number of the unit within the relevant component; *m* – corresponds to the item number of the basic element, included into the relevant unit);

$C_{ijlkm}^{main.mat.}$ – accumulative value of the main materials including: rolled metal products, parts and components, from which *m* basic element is produced;

$C_{ijklm}^{add.mat.}$ – accumulative value of additional or accessory materials, including: metalware, nuts, rivets, welding wire, paint, oxygen, carbon dioxide, etc., from which *m* basic element is produced;

C_{ijlkm}^{Man} – accumulative manpower for *m* basic element;

C_{ijlkm}^{E} – aggregate energy consumption (electric power, compressed air, etc.) for *m* basic element production;

$C_{ijlkm}^{indir.}$ – accumulative indirect costs for production of *m* basic element.

Depending on what is the final product of the enterprise or the organization there can be added the general production expenditures, administrative ones or other costs.

$$C_{ijlk} = \sum_{k=1}^{a} C_{ijlkm} + C_{ijlk}^{add.mat.} + C_{ijlk}^{Man} + C_{ijlk}^{E} + C_{ijlk}^{indir.} \qquad (5.4.)$$

C_{ijlk} – cost of *k* unit;

$\sum_{k=1}^{a} C_{ijlkm}$ – accumulative value of the basic elements, included into the constitution of *k* unit;

$C_{ijlk}^{add.mat.}$ – accumulative value of additional or accessory materials, from which *k* unit is produced;

C_{ijlk}^{Man} – accumulative manpower for *k* unit production;

C_{ijlk}^{E} – aggregate energy consumption for *k* unit production;

$C_{ijlk}^{indir.}$ – accumulative indirect costs for *k* unit production.

$$C_{ijl} = \sum_{k=1}^{b} C_{ijlk} + C_{ijl}^{add.mat.} + C_{ijl}^{Man} + C_{ijl}^{E} + C_{ijl}^{indir.} \quad (5.5.)$$

C_{ijl} –the prime cost of l constituent;

$\sum_{k=1}^{b} C_{ijlk}$ – accumulative value of units, included into the constitution of l constituent;

$C_{ijl}^{add.mat.}$ – accumulative value of additional or accessory materials, from which l constituent is produced;

C_{ijl}^{Man} – accumulative manpower for l constituent production;

C_{ijl}^{E} – aggregate energy consumption for l constituent production;

$C_{ijl}^{indir.}$ – accumulative indirect costs for l constituent production.

$$C_{ij} = \sum_{k=1}^{d} C_{ijl} + C_{ij}^{add.mat.} + C_{ij}^{Man} + C_{ij}^{E} + C_{ij}^{indir.} \quad (5.6.)$$

C_{ij} – prime cost of j module;

$\sum_{k=1}^{d} C_{ijl}$ – accumulative value of the constituents, included into the constitution of j module;

$C_{ij}^{add.mat.}$ – accumulative value of additional or accessory materials, from which j module is produced;

C_{ij}^{Man} – accumulative manpower for j module production;

C_{ij}^{E} – aggregate energy consumption for j module production;

$C_{ij}^{indir.}$ – accumulative indirect costs for j module production.

$$C_{i} + \sum_{k=1}^{n} C_{ij} + C_{i}^{add.mat.} + C_{i}^{Man} + C_{i}^{E} + C_{i}^{indir.} \quad (5.7.)$$

C_{i} – prime cost of i freight wagon;

$\sum_{k=1}^{n} C_{ij}$ – accumulative value of modules, included into i freight wagon;

$C_{i}^{add.mat.}$ – accumulative value of additional or accessory materials, used at assembly of i freight wagon;

C_{i}^{Man} – accumulative manpower used for assembly of i freight wagon;

C_i^E – aggregate energy consumption for production, used for assembly of i freight wagon;

$C_i^{indir.}$ – accumulative indirect costs for i freight wagon production.

The following stages may be characterized as specific for the supporting systems of the freight wagons as they are devoted to identification and estimation of the excess strength reserve. We determined the excess strength reserve based on the data of theoretical and experimental researches of the selected models of the open wagons. In general, the procedure to define the excess strength reserve includes the following actions. We identify first both theoretically and experimentally the maximal values of the loads within the elements in accordance with the 1st, 2nd, 3rd calculation modes [12-17, 19, 22, 24], as well as in the mode of collision in accordance with the freight wagon design code. After that, the minimal initial strength reserve should be identified in accordance with each calculation mode on the base of comparison of the obtained values with the acceptable ones, and respectively the minimal values should be selected. Furthermore, we identify the minimal acceptable values of the basic strength characteristics, that is, the moment resistances of the cross-sections. The next step is determining of values the moment resistance of the studied profiles at the end of the designed service life (for example, it makes 22 years for open wagons), this is performed with application of the developed mathematical dependencies, through the simulation of the geometrical parameters of the cross-sections with consideration of the corrosion rates. Finally, through comparison of the acceptable values of the moment resistance with their characteristics at the stage approaching the end of the designed service life, we identify the excess strength reserve.

Upon identification of the functional elements values, there should be determined the functional areas of the greatest concentration of the object costs while the search for more reasonable and optimal design and production solutions becomes the new task to solve:

1) Search and Exploration Stage: the search for improved engineering solutions, their mathematical modeling, the search of optimal indices and parameters of the engineering solutions, experimental researches;

2) Development and Implementation of the Analysis Results. The scope of works at this stage is implied by its name.

5.3.3. Example of Functional-Cost Analysis for Wagon End of the Railway Open Wagons

As the example how the proposed procedure of the functional-cost analysis can be applied, below is presented the description for the relevant research of the body wagon end frame of the most widespread and demanded type of the freight wagons, called as general-purpose open wagons. Within this framework, we have singled out one of the most widespread basic structure of the wagon end frame (figure 5.7) among the contemporary open wagon models produced by CIS countries manufacturers. The frame of the studied wagon end consists of the top cord (molded section with rectangular cross section of 140x110x7 mm in size, according to the Ukrainian Technical Specification 27.3-00190319-1316-2004, welded along the cross-section into the box), side stake (channel of 12П according to DSTU 3436), horizontal top chord, horizontal middle chord, horizontal bottom chord (made of profile of wagon stake in agreement with GOST 5267.6-90), intermediate stake and bottom stake (the stakes are molded section channel of *30x80x8* mm in size).

Moreover, the main function of the open wagon end frames is their performance within the constitution of the general bearing system of the wagon,

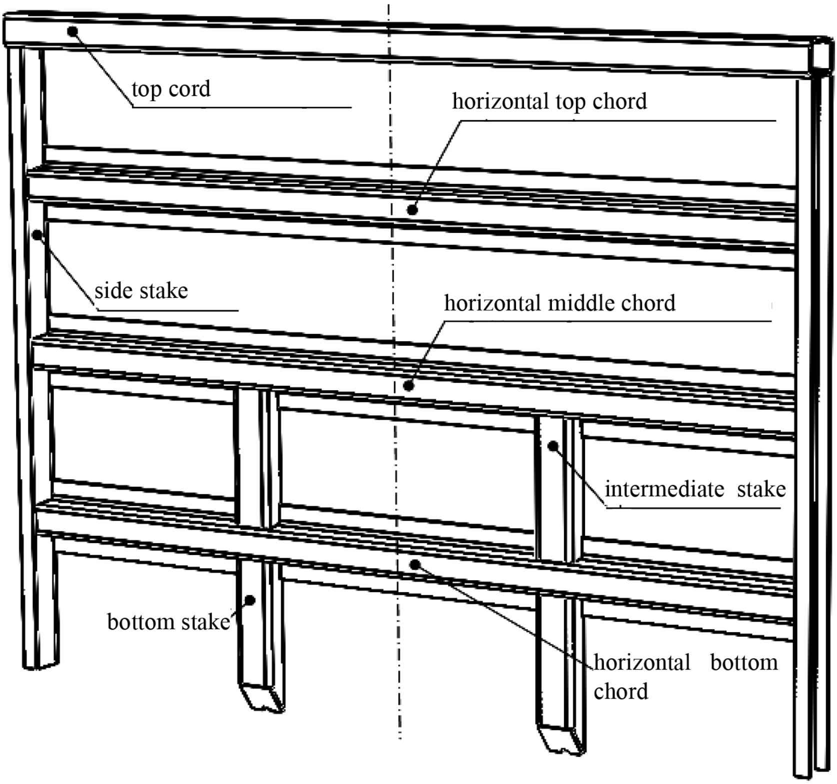


Figure 5.7. Open Wagon End Frame

directed at loads accommodation, emerging into the process of operation without permanent deformation. Moreover, the elements of the open wagon end frame must effectively withstand the action of the atmospheric factors within the entire designed service life of 22 years. As the main criteria of further evolution of the end frames one may define reduction in costs, reduction in material consumption and improvement on the parameters of the operational reliability.

Eventually, the technical order for the functional-cost analysis of open wagon end frames to carry out is the following: 1) functional-cost analysis must be performed for the entire frame of the wagon end; 2) the priority objective is to reduce the prime cost of the wagon end frame but meet the requirements for the strength and the operational reliability. Table 4.5 presents the functions of the basic elements selected for the research on open wagon end frame.

Table 5.5

Analysis of the Functions of the Basic Elements Selected for the Research on Open Wagon End Frame

Item No.	Basic element: object, at which its action is directed	Function of the Basic Element with Consideration of Special Conditions and Restriction H
1	B_{11121} – top cord: B_{11122}; B_{11128} – lining; B_{1111} – wagon side; G_2 – cargo.	F^1_{11121} – interaction with B_{11122} at load accommodation; $F^{1(2)}_{11121}$ – leak-free performance for covering; B_{11122}; F^2_{11121} – interaction with B_{11128} at load accommodation; F^3_{11121} – interaction with B_{1111} at load accommodation; F^4_{11121} – interaction with G_2 at body loading, at transportation of the cargo, which fully fills the body. Provided that the requirements of $H_{111211}...H_{11121r}$ are met.
2	B_{11122} – side stake: B_{11121}; B_{11123}; B_{11124}; B_{11125}; B_{1111}; B_{1124} – head stock; G_2 – cargo.	F^1_{11122} – interaction with B_{11121} at load accommodation; F^2_{11122} – interaction with B_{11123} at load accommodation; $F^{2(2)}_{11122}$ –leak-free performance for covering (B_{11123}); F^3_{11122} – interaction with B_{11124} at load accommodation; $F^{3(2)}_{11122}$ – leak-free performance for covering (B_{11124}); F^4_{11122} – interaction with B_{11125}; $F^{4(2)}_{11122}$ – leak-free performance for covering (B_{11125}); F^5_{11122} – interaction with B_{11128} at load accommodation; F^6_{11122} – leak-free connection and interaction with B_{1111} at load accommodation; F^7_{11122} – interaction with B_{1124}; F^8_{11122} – interaction with G_2, if the requirements of $H_{111221}...H_{11122r}$ are met.
3	B_{11123} – horizontal top chord: B_{11122}; B_{11128}; B_{111212}-B_{111214} – tie down elements.	F^1_{11123} – interaction with B_{11122} at load accommodation; F^2_{11123} – interaction with B_{11128} at load accommodation; F^3_{11123} – interaction with B_{111212}- B_{111214} through B_{11128}, if the requirements of $H_{111231}...H_{11123r}$ are met.

Item No.	Basic element: object, at which its action is directed	Function of the Basic Element with Consideration of Special Conditions and Restriction H
4	B_{11124} – horizontal middle chord: B_{11122}; B_{11126}; B_{11128};	F^1_{11124}– interaction at load accommodation with B_{11122}; F^2_{11124}– interaction at load accommodation with B_{11126}; $F^{2(2)}_{11124}$–leak-free performance for covering B_{11126}; F^3_{11124} – interaction at load accommodation with B_{11128}, if the requirements of $H_{111241}...H_{11124r}$ are met.
5	B_{11125} – horizontal bottom chord: B_{11122}; B_{11126}; B_{11127};B_{11128};	F^1_{11125}– interaction with B_{11122} at load accommodation; F^2_{11125}– interaction with B_{11126} at load accommodation; $F^{2(2)}_{11125}$–leak-free performance for covering B_{11126}; F^3_{11125}– interaction with B_{11127} at load accommodation; $F^{3(2)}_{11125}$– leak-free performance for covering B_{11127}; F^4_{11125}– interaction with B_{11128} at load accommodation, if the requirements of $H_{111251}...H_{11125r}$ are met.
6	B_{11126} – vertical middle stake: B_{11124}; B_{11125}; B_{11128}.	F^1_{11126}– interaction with B_{11124} at load accommodation; F^2_{11126}– interaction with B_{11125} at load accommodation; F^3_{11126}– interaction with B_{11128} at load accommodation, if the requirements of $H_{111261}...H_{11126r}$ are met.
7	B_{11127} – vertical bottom stake: B_{11125}; B_{11128}; B_{1124}.	F^1_{11127}– interaction with B_{11125} at load accommodation; F^2_{11127}– interaction with B_{11128} at load accommodation; F^3_{11127}– interaction with B_{1124} at load accommodation, if the requirements of $H_{111271}...H_{11127r}$ are met.

The information, summarized in table 5.5, becomes the base for the development of the structural-functional model of the frame in the form of the relevant chart (refer to figure 5.8). The apices of this chart are the units and the basic elements of the structure, as well as object G_2. The structural connections between the elements are shown in the firm lines. The functions of the elements are presented in the form of the chart ribs in curved lines. They come out of the apices, which stand for the elements that perform relevant functions. The designations of the apices-elements, apices-objects and ribs in the chart match with the defined and described ones in table 5.5.

We do not show those additional functions (see below) that coincide with the main functions in their orientation due to considerable complexity of the chart (figure 5.8) and high concentration of the information.

Having analyzed the functions of the wagon end frame elements, we conclude that they may be classified by the following way: 1) main functions are characterized by preservation of the cargo at the wagon operation and performed

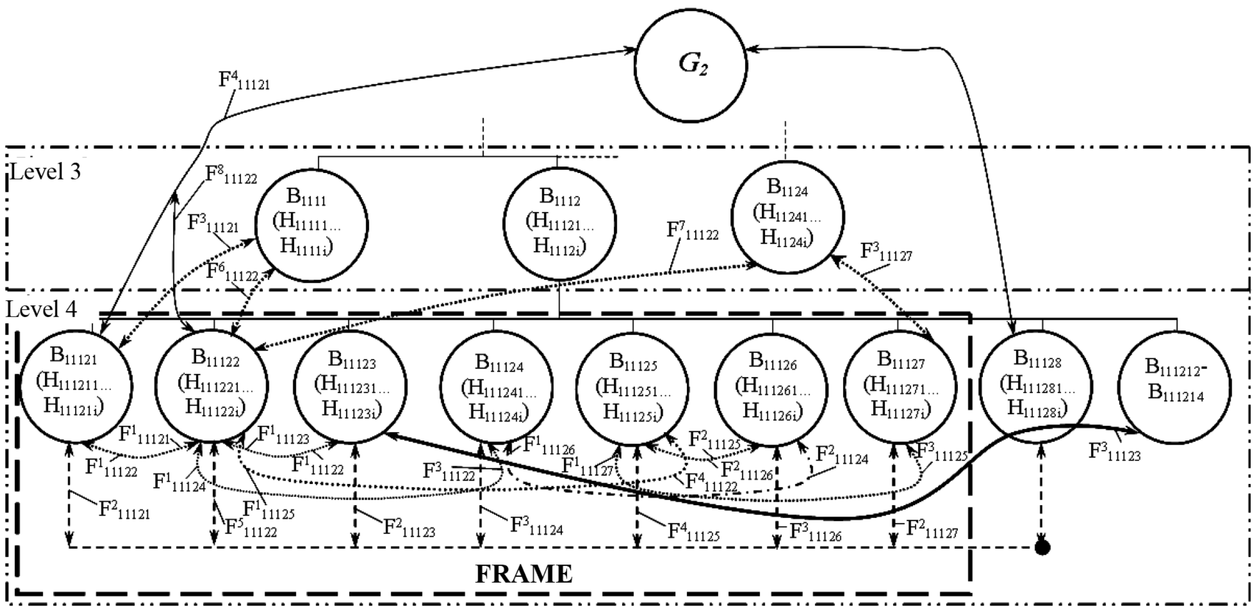


Figure 5.8. Structural-Functional Model of the Contemporary Hypothetical General-Purpose Open Wagon End Frame

by the frame together with the lining: F^{1}_{11121}, F^{2}_{11121}, F^{3}_{11121}, F^{1}_{11122}, F^{2}_{11122}, F^{3}_{11122}, F^{4}_{11122}, F^{5}_{11122}, F^{6}_{11122}, F^{1}_{11123}, F^{2}_{11123}, F^{1}_{11124}, F^{2}_{11124}, F^{3}_{11124}, F^{1}_{1112}, F^{2}_{11125}, F^{3}_{11125}, F^{4}_{11125}, F^{1}_{11126}, F^{2}_{11126}, F^{3}_{11126}, F^{1}_{11127}, F^{2}_{11127}; 2) additional functions are as follows: $F^{1(2)}_{11121}$, F^{4}_{11121}, $F^{2(2)}_{11122}$, $F^{3(2)}_{11122}$, $F^{4(2)}_{11122}$, F^{7}_{11122}, F^{8}_{11122}, F^{3}_{11123}, $F^{2(2)}_{11124}$, $F^{2(2)}_{11125}$, $F^{3(2)}_{11125}$, F^{3}_{11127}; 3) odd functions are absent, that may be explained by evolution of the four-axle open wagon frame structure during the period of more than a century.

Eventually, based on the approximated costs of 2014 and the above reported procedure of the cost formation (formula 4.3-4.7), we have defined the maximal (existing) costs and minimal (defined with consideration of perspective design) costs of the wagon end frame elements. The obtained data are shown in table 5.6 and they evidence that the area of the greatest concentration of the costs may include the sections of horizontal chords and top cord. Such situation may be explained by the fact that these basic elements are produced from the special wagon metal rolled products and, as a consequence, have increased value. The presented above procedure of excess strength reserve identification allows us to define the relevant costs and the shares of excess costs (product of excess strength reserve with the relevant costs). The results of the listed above operation are given in table 5.7.

Table 5.6

Summarized Sheet of the Functional Elements value

Item No.	Functions	Elements	Value, UAH		Relevant difference, %	Value of 1 kg of structure component, UAH/kg
			Minimal possible	Maximal acceptable		
1	F^{1}_{11121}; F^{2}_{11121}; F^{3}_{11121}; F^{4}_{11121}.	Top cord (B_{11121})	411	544	24.4	7.37
2	F^{1}_{11122}; F^{2}_{11122}; F^{3}_{11122}; F^{4}_{11122}; F^{5}_{11122}; F^{6}_{11122}; F^{7}_{11122}; F^{8}_{11122}.	Side stake (B_{11122})	121	128	5.5	2.92
3	F^{1}_{11123}; F^{2}_{11123}; F^{3}_{11123}.	Horizontal top chord (B_{11123})	428	656	34.8	7.88
4	F^{1}_{11124}; F^{2}_{11124}; F^{3}_{11124}.	Horizontal middle chord (B_{11124})	428	656	34.8	7.88
5	F^{1}_{11125}; F^{2}_{11125}; F^{3}_{11125}; F^{4}_{11125}.	Horizontal bottom chord (B_{11125})	428	656	34.8	7.88
6	F^{1}_{11126}; F^{2}_{11126}; F^{3}_{11126}.	Vertical middle stake (B_{11126})	37	42	11.9	2.82
7	F^{1}_{11127}; F^{2}_{11127}; F^{3}_{11127}.	Vertical bottom stake (B_{11127})	40	46	13.0	2.90

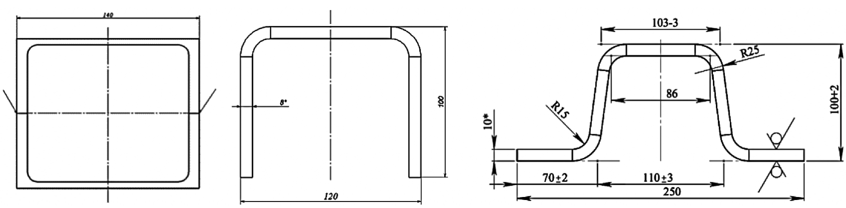
From table 5.7 one can see that functional area of the excess cost greatest concentration is the group of wagon end horizontal chords and top cord, which indicates the necessity of their improvement. Taking into account the foregoing and the base of the multiple researches, we suggest that the top cord should be made from welded between each other channels (figure 5.9, *a*), wagon end horizontal top chord should be made from roll-formed channel (figure 5.10, *b*), and the horizontal middle and the bottom chords should be made the roll-formed analogue of the wagon stake cross-section (figure 5.10, *c*).

Table 5.7

Shares of the Elements Excess Costs

№ Item No.	Functions	Elements	Excess strength reserve, %	Relative costs, %	Shares of excess costs, %
1	F^1_{11121}; F^2_{11121}; F^3_{11121}; F^4_{11121}.	Top cord (B_{11121})	16.2	21.7	35.1
2	F^1_{11122}; F^2_{11122}; F^3_{11122}; F^4_{11122}; F^5_{11122}; F^6_{11122}; F^7_{11122}; F^8_{11122}.	Side stake (B_{11122})	48.8	6.4	31.2
3	F^1_{11123}; F^2_{11123}; F^3_{11123}.	Horizontal top chord (B_{11123})	52.1	22.6	117.8
4	F^1_{11124}; F^2_{11124}; F^3_{11124}.	Horizontal middle chord (B_{11124})	39.1	22.6	88.3
5	F^1_{11125}; F^2_{11125}; F^3_{11125}; F^4_{11125}.	Horizontal bottom chord (B_{11125})	30.3	22.6	68.6
6	F^1_{11126}; F^2_{11126}; F^3_{11126}.	Vertical middle stake (B_{11126})	54.4	2.0	10.6
7	F^1_{11127}; F^2_{11127}; F^3_{11127}.	Vertical bottom stake (B_{11127})	61.1	2.1	12.9

Finally, the suggested solutions give the possibility to considerably reduce the costs of the open wagons production as much as almost by UAH 2500.



a) top cord made of channels *b)* horizontal bottom chord *c)* horizontal middle and bottom chords

Figure 5.9. Perspective production of the wagon end frame elements

The functional-cost analysis has brought the conclusion that the structural-functional chart does not contain the odd elements. It is also defined that the functional area of the greatest concentration of the object costs is the top horizontal chords, middle horizontal chords and bottom horizontal chords (figure 5.7) as well as top cord produced from rolled sections. The economical potential of this open wagon design direction is rather great if consider their widespread usage.

CONCLUSIONS

The results inherent to the development of the theoretical foundations for synthesis of conceptually new modules of the rolling stock are in identifying the following break-through working hypothesis for the rolling stock structure improvements:

- transfer from the statically defined to the statically undefined structures of resource determining areas and those of possible destruction with the objective to reduce the resulting loads and redistribution of loads;
- development of the structures with loaded units without odd connections, excess strength reserve and excess stiffness; flexible connections introduction may serve as one of the examples;
- development of structural schemes, where the supporting elements are maximally operated for compression and tension instead of bending and twisting;
- development of supporting elements as connected structural linings with the possibility to form sandwich panels with directed properties;
- development of equal stress state and preliminary stressed structures of supporting elements aiming at reduction in the stress level and respectively reduction in structure weight;
- introduction of the security elements in order to ensure temporary operability of the structure elements in accident situations;
- introduction of multifunctional elements, particularly, stress-dissipative supporting elements that encompass functions of rigid connection elements with flexible and damping, in order to considerably reduce the weight, the number of structure elements and the amount of connections;
- development of the structures with indicators of critical states and possibility for autonomous self-diagnostics.

REFERENCES

1. Butko, T. V., Prokhorchenko A. V., Kyman A. (2015) Formalization of the technology of arranging tactical group trains. *Eastern-European Journal of Enterprise Technologies*. Vol 4. No 3 (76), p.p. 38–43.

2. Fomin, O. (2014) Modern requirements to carrying systems of railway general-purpose gondola cars. *Scientific and technical journal "Metallurgical and Mining Industry"*. No 5, p.p. 31-43.

3. Fomin O. V., Gorbunov N.I., Lovskaya A.A. (2016) Prospective concept of the draft system of open boxcars. *Visnyk Kremenchutskoho natsionalnoho universytetu imeni Mykhaila Ostrohradskoho* [Bulletin of Kremenchuk Mykhailo Ostrogradskyi National University]. Kremenchuk: KRNU. No 6 (101) p.1, p. p. 76-85.

4. Gorbunov M., Domin R., Kovtanec M., Kravchenko K. (2016) The multifunctional energy efficient method of cohesion control in the "wheel-braking pad-rail" system. *Prace Naukowe Politechniki Warszawskiej*, p.p. 115–126.

5. Gorbunov. N., Kravchenko E., Demin R., Nogenko O., Prosvirova O. (2013) Analysis of the constructive features of railway brakes and methods of improving the process of their functioning. *TEKA Commission of Motorization and Power Industry in Agriculture.* Vol. 13, No 5, p.p. 63–67.

6. Lovskaya A., Ryibin A. (2016) The study of dynamic load on a wagon-platform at a shunting collision. *Eastern-European Journal of Enterprise Technologies*. Vol. 3. No 7 (81), p.p. 4–8.

7. Myamlin S., Lingaitis L. P., Dailydka S., Vaičiūnas G., Bogdevičius M., Bureika G., Myamlin S. (2015). Determination of the dynamic characteristics of freight wagons with various bogie. *Transport*. Vol. 30. No 1, p.p. 88–92.

8. Salamatov Yu.(1999). *TRIZ: The Right Solution at the Right Time: A Guide to Innovative Problem Solving.* The Netherlands. Insytec, 256 p.

9. Tartakovskyi E., Gorobchenko O., Antonovych A. (2016) Improving the process of driving a locomotive through the use of decision support systems. Eastern-European Journal of Enterprise Technologies. Vol. 5, No 3 (83), p.p. 4–11.

10. Amirov Yu. (1991) *Osnovy konstruirovaniya: Tvorchestvo - standartizatsiya - ekonomika: Spravochnoye posobiye* [Design fundamentals: Creativity - Standardization – Economics: Reference Guide]. Moscow. Publishing House of Standards, 39 p.

11. Gorbunov N.I. (2006) *Teoriya i prakticheskaya realizatsiya sistemnogo podkhoda pri sozdanii ekipazhnoy chasti lokomotiva: dis… d-ra tekhn. nauk* [Theory and practical implementation of the systematic approach in the creation of

locomotive underframe: dissertation of Doctor of Technical Sciences: 05.22.07]. Volodymyr Dahl East Ukrainian National University. Lugansk, 437 p.

12. GOST 33211-2014 (2016) *Vagony gruzovyye. Trebovaniya k prochnosti i dinamicheskim kachestvam*. [Freight wagons. Requirements for durability and dynamic qualities]. [Valid from 22.12.2014]. Moscow. Standardinform, 54 p.

13. DSTU 7598: 2014 *Vahony vantazhni. Zahalni vymohy do rozrakhunkiv ta proektuvannya novykh i modernizovanykh vahoniv koliyi 1520 mm (nesamokhidnykh)* [Freight cars. General requirements for calculations and design of new and upgraded cars for rail of 1520 mm (non-self propelled)].

14. DSTU 7774: 2015 *Vahony pasazhyrski mahistralni lokomotyvnoyi tyahy. Zahal'notekhnichni normy dlya rozrakhuvannya ta proektuvannya mekhanichnoyi chastyny vahoniv* [Passenger wagons of mainline locomotive thrust. General technical rules for calculating and designing the mechanical part of wagons].

15. Lukin V.V., Shadur L.A., Koturanov V.I., Khokhlov A.A., Anisimov P.S. (2000) *Konstruirovaniye i raschet vagonov* [Design and calculation of wagons]. Moscow. UMK MPS of Russia, 731 p.

16. *Mezhgosudarstvennyy standart (proyekt). Vagony gruzovyye i passazhirskiye. Metody ispitaniy na prochnost i dinamicheskiye kachestva* [Interstate Standard (draft). Freight and passenger cars. Methods of tests of strength and dynamic qualities].

17. *Normy dlya rascheta i proyektirovaniya vagonov zheleznykh dorog MPS kolei 1520 mm (nesamokhodnykh) i izmeneniya i dopolneniya* [Norms for calculation and design of railroad cars of the Ministry of Railways for rail of 1520 mm (non-self-propelled) and modifications and additions]. Moscow. GosNIIV – VNIIZhT. 1996, 319 p.

18. Polovkin A. I. (1988) *Osnovy inzhenernogo tvorchestva: Ucheb. Posobiye dlya studentov vuzov*. [Fundamentals of engineering creativity: Manual for university students]. Moscow. Mashinostroenie, 368 p.

19. RD 24.050.37-95 (1995) *Vagony gruzovyye i passazhirskiye. Metody ispytaniy na prochnost i khodovyye kachestva*. [Freight and passenger cars. Test methods for strength and running performance]. Moscow. GosNIIV.

20. Tkachenko V. P., Sapronova S. Yu., Kulbovskii I.I., Zub E.P. (2016) *Opir rukhu i kerovanist reykovykh ekipazhiv: Monohrafiya* [Resistance to movement and handling of railroad undercarriages: Monograph]. Kyiv. DETUT, 160 p.

21. Fomin O.V. (2016) *Rozvytok naukovykh osnov stvorennya ta efektyvnoho vykorystannya vantazhnykh vahoniv: dys. ... d-ra tekhn. nauk: 05.22.07* [Development of scientific foundations for the creation and efficient use of freight cars: dissertation of Doctor of Technical Sciences: 05.22.07]. State Economic and Technological University of Transport, 381p.

22. Fomin O.V. (2014) *Doslidzhennya defektiv ta poshkodzhen nesuchykh system zaliznychnykh napivvahoniv: monohrafiya* [Investigation of defects and damages of carrying systems of railway open wagons: monograph]. Kyiv. SETUT, 299 p.

23. Fomin O.V. (2013) Kontseptsiya idealnykh kuzoviv napivvahoniv [Concept of ideal bodies of open wagons]. *Visnyk Skhidnoukrayinskoho natsionalnoho universytetu imeni Volodymyra Dalya: naukovyy zhurnal* [Bulletin of Volodymyr Dahl East Ukrainian National University: scientific journal]. Lugansk. Volodymyr Dahl East Ukrainian National University. No 4 (193), p.p. 267-271.

24. Fomin O.V. (2013) *Optymizatsiyne proektuvannya elementiv kuzoviv zaliznychnykh napivvahoniv ta orhanizatsiya yikh vyrobnytstva: monohrafiya* [Optimization design of body elements of railway open wagons and organization of their production: monograph]. Donetsk. DonIZT UkrDAZT, 251p.

25. Fomin O.V. (2015) Pidvyshchennya stupenya ideal'nosti vantazhnykh vahoniv ta prohnozuvannya stadiy yikh evolyutsiyi [Increasing the degree of perfection of freight wagons and forecasting the stages of their evolution]. *Naukovyy visnyk Natsionalnoho hirnychoho universytetu* [Scientific Bulletin of the National Mining University]. Dnipropetrovsk. NMU. No 3, p.p. 68-76.

FOR NOTES

Scientific Publication

Doctor of Engineering Sciences MYKOLA I. GORBUNOV
Doctor of Engineering Sciences OLEKSII V. FOMIN
VIACHESLAV V. KOVALENKO
PhD in Engineering Sciences ROSTYSLAV YU. DOMIN

THEORETICAL FOUNDATIONS FOR CONCEPTUALLY NEW ROLLING STOCK MODULES

(Part 1)

Monograph

English version

Approved for publishing ??.??.2017

Format 60x84/16. Printed at Gestetner 6123CP risograph.

Conventional printed pages 18.75 of 300 copies

Order No.21-14.

Agreed-upon price

Printing house ????????????
Certificate of publishing business agent registration in the PC No. ?????
???????????