 ISSN 2226-3780

UDC 656.615.078.111/.117

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ЗАБЕЗПЕЧЕННЯ ПОГОДЖЕНОГО УПРАВЛІННЯ ПРОЦЕСОМ ПЕРЕВАЛКИ ВАНТАЖІВ У ЗАГАЛЬНОТРАНСПОРТНИХ ВУЗЛАХ

У статті запропоновано оригінальний підхід до забезпечення погодженого управління транспортними вузлами, заснований на сполученні методології класичної науки оптимального управління й конструктивними ідеями прогресуючих у цей час нових концепцій ділового поводження й соціального управління. При цьому встановлено, що реалізацію запропонованого підходу необхідно здійснювати у два етапи: спочатку необхідно погодити параметри процесу перевалки вантажів, а потім забезпечити здійснення цього процесу в оптимальному режимі.

Ключові слова: *транспортний вузол, перевалка вантажів, оптимальне управління, партнерська взаємодія, оптимізація вантажоперевалювального процесу.*

1. Introduction

At the turn of the XX and XXI centuries, scientific researches in the field of integrated transport management theory have intensified in Ukraine and Russia. This trend has become especially evident in studies, aimed at improving the theory and methods of management organization of the junction points of related transport modes as systems, consisting of sets of interrelated elements [1] and called at that time general transport hubs (GTH). Initially, these studies were based on the concepts of classical optimal control theory, developed last century. Then, under the influence of global development trends of transport science, in studies of Ukrainian and Russian specialists there has been a shift from the principles of classical management science with reorientation to new theories of business conduct — transport logistics, partnership marketing in conjunction with the concepts of network forms of inter-firm cooperation, clustering, developing strategic alliances, interaction between business and government.

The same years, the stated in [2] idea of creating «marine transport hub» region [3, 4] within the seaport, under which it was proposed to understand the set of public and private companies, which are aimed at servicing cargo- and ship owners during the implementation of cargo transshipment process (CTP) was actualized.

From the foregoing, it is apparent that to date contradictory situation in studying complex problems of transport hub management organization has formed. On the one hand, the traditional management paradigm of hubs and their interpretation as GTH is not officially rejected. On the other hand, the idea of interpreting hubs as marine transport hubs (MTH) with the transition to using the above-mentioned new business conduct theories for inter-hub management is actively put forward. In both cases, in all the above-mentioned works, the problem of creating the management *coordination* mechanism within the GTH (MTH) is just mentioned.

Meanwhile, the stated problem is equally relevant when using any approach to the transport hub management, whether classical optimal control methodology or market conduct philosophy, or a combination of both approaches, and no matter how transport hubs are interpreted — as GTH or MTH. In this situation, it is the most logical to conclude that it is necessary to consider this particular issue as paramount for constructing the effective CTP management mechanism in transport hubs and determine its elaboration as a major problem of this study.

2. Problem statement

From the above, it is easy to conclude that the correct statement of the problem of ensuring coordinated CTP management in GTH is possible only from the positions, which take into account its close connection with the current scientific and practical problems, solved in the national projects. The appropriateness of such assertion is first of all indicated by the fact that more than half of the cargo transportation time is accounted for their loading and unloading at loading, unloading and transshipment points. The costs of these operations about 4 times exceed the costs for cargo transportation by trunk transport modes.

The main reason for the marked negatives in transport operation lies in slowing the cargo transportation up to a stop because of the occurrence and accumulation of non-coordination in the operation of related transport modes, which leads to non-synchronous arrival of their rolling stock in the GTH. That is why there are «abandoned» railcars on rail landfills near seaports, imposition of convention prohibitions and partial restrictions on bulk cargo shipment to the ports, demurrage of vessels, wagons and cars with cargos and awaiting cargos, accumulation of unclaimed cargos at ports. As a result, almost all participants of the logistics chain of cargo delivery and transport services bear losses, measured in total by seven-digit numbers.

The above findings underline the fact that MTH are «the last» opportunity if not to eliminate, but at least partially remove «movement» disproportions in the operation of related transport modes. It can be achieved, obviously, only under condition of ensuring the fullest possible coordination in the work of co-operating enterprises of GTH with the joint organization and implementation of CTP.

3. Analysis of the literature

Before proceeding directly to analytical review of literary sources, pay attention to the following two facts that are important in terms of methodology. The first one is related to the presence of various approaches to the formal presentation of transport hubs. Indeed, along with a general concept of GTH, which fully reflects the integrated (inter-sectoral production) nature of transport hubs, some experts prefer MTH, treating them as associations of manufacturing enterprises (stevedoring companies) and service organizations (forwarding, agency and other companies) as well as government bodies and intermediary structures [2]. This approach, in our opinion, cannot have definite estimate. Indeed, on the one hand, including service organizations to the subjects of transport hubs is a quite acceptable step. However, on the other hand, excluding port railway stations and rolling stock of related transport modes from transport hubs leads to rejecting the concept of «transport hub» as «intersection» point of various transport means. And this, in turn, causes substitution of intersystem transshipment process by local reloading process of ports that obviously cannot be accepted because management mechanisms of these processes are based on different presuppositions.

From the foregoing, it becomes apparent that objectively there are no substantial grounds for the transition from the GTH concept to the MTH concept. For this reason, only GTH will be further considered in the paper provided that agency and forwarding companies that are really actively involved in the CTP organization and implementation will be presented in their structure.

The second factor reflects the changes in the researchers' orientation on the methodological tools, used in constructing cargo transshipment process management mechanism, implemented in GTH. As noted above, during the second half of the last century, proponents of classical management theory focused on constructing economic-mathematical models of CTP management in terms well developed mathematical disciplines (mathematical programming, queuing theory, scheduling) and simulation modeling as well.

In the beginning of this century, they shifted to the approaches to the transport hub management organization, proposed by Western European scientists based on a methodical arsenal of the theory of interacting systems, morphological and cognitive modeling, artificial intellect, system programming and multi-agent optimization [5–8]. In both cases, the researchers paid very little attention to ensuring the coordinated CTP management.

The validity of the above statements is easy to verify by having familiarized with publications in the field of study, published recently.

Thus, the dissertation research [9], performed in the manner of classical management interpretation tradition concerns the GTH, consisting of two enterprises only — port (sea or river) and port railway station. Herewith, cargo transshipment is considered only for one CTP stage, which runs in the port when loading vessels from railcars, i. e., only directly. The work under analysis contains a formal description of the GTH (or rather only its port unit) with using the theory of interacting sequential processes [10], closely related to the theory of sequential systems [11] as a methodological tool. Such an approach to the GTH operation process formalization is appealing from the theoretical standpoint since it allows quite finely render the vessel loading process. However, its practical value cannot be considered as high because of an extremely cumbersome implementation procedure. Still, a more significant feature of this approach lies in the fuzziness of its criterion base and virtually full absence of connection with the market philosophy of business conduct of the GTH subjects in relations both among themselves, and with customers.

The work [12], which gives an analytical overview of the methodological arsenal of optimal management theory in terms of the possibility and feasibility of applying existing methods for GTH operation simulation was performed in a similar statement (for the complex port — station and the vessel loading process in the port). According to the analysis results it was concluded that the methods of cognitive and morphological analysis are the most promising for this purpose. This assertion is illustrated in [12] by academic example of morphological modeling of the vessel loading process at the port, but without indicating the way of implementing the model thus obtained. Consequently, the question concerning the actual value of the approach, proposed in the characterized work remains open from both the theoretical, and practical standpoints.

The work [13], in which an attempt to combine rational ideas of traditional and new approaches to the GTH management organization was made, is boundary in a certain sense. The first of the indicated directions — traditional — is presented in this work almost in the same statement as in [12], i. e., with a focus on selecting a morphological and cognitive modeling in combination with scenario-based approach to the hub activity planning as a suitable methodological tool for constructing the GTH management mechanism. The second and more valuable direction — market — is reflected in [13] as a substantiation of one of fundamentally possible ways of posing the problem of reconciling the interests of GTH subjects in the course of CTP organization and implementation. This part of the developmental work, contained in the given research is performed in terms of the theory of assessing the impact of feedback in the management mechanism on the operation of the managed object with the recommendation on further transition to implementing the method for vector optimization of CTP within GTH. Herewith, all marked ideas are considered, in the accepted phrase, only in the order of the problem statement.

Indicated in [13] market accents in substantiation of the GTH management mechanism were developed in the studies of recent five years in developing the methodological formation bases of MTH, interpreted as a network partnership institution [2].

The key idea of the latest work consists in justifying the possibility of using the concept of partnership marketing [14] under the name of relationship marketing as a methodological basis for developing the MTH management mechanism. Such an initiative is argued in [2] by the urgent need to move MTH subjects to the paradigm of creating a joint value based on establishing and maintaining long-term business relationships among all participants of cargo delivery by the «door — to door» scheme.

At collective consideration of transport hub management concepts, characterized in [9, 10, 12, 13] it becomes apparent that none of them gives serious attention to the problem of ensuring *coordinated* actions of GTH subjects, so that there is an objective need to find opportunities to eliminate this some kind of «white spot» in the complex transport management theory.

4. Methodology for ensuring the coordinated cargo transshipment process management in transport hubs

4.1. Assumptions. To achieve the target objective of the research, it is necessary to take into account that in their work any related enterprises, including transport, become closely associated and interdependent. As a result, a complex interweaving of the business interests of related enterprises occurs, which objectively presupposes the need to maintain effective contacts between enterprises of transport hubs in CTP organization and implementation.

Since 1930-ies, activities on ensuring such contacts are called differently: coordination, interaction, or both as a single unit and associated with management. Thus, both concepts in one case are equated, and in another — delimited, defined in broad and narrow sense (by the transport process as a whole and its individual stages), treated in relation to the sets of each transport mode (sectoral statement) and related transport modes including transport hubs (inter-sectoral statement).

This kind of uncertainty arises from synonymous redundancy in defining the considered concepts, which is explained mainly by the ambiguity of their interpretation in the theoretical and methodological sense. As a result, linguistic frameworks of interpreting both concepts are blurred, which naturally causes unproductive discussions and may lead to incorrect scientific conclusions.

The outlined status quo in defining the concepts of coordination and interaction as tools to achieve coordinated transport management persists up to the present time. Herewith, the question of the methodological bases of coordination and interaction as components of the problem of constructing the GTH management mechanism remains beyond the vision of researchers of complex transport problems.

Based on the foregoing, an attempt to fill this gap and approach to solving the problem of ensuring the coordinated GTH management from positions, combining the ideas of traditional and new theories of ensuring the effective functioning of market participants, specifically, partnership marketing [14], social partnership [15] and linear programming was made. With this approach, there is a need to divide (decompose) the investigated problem into two interrelated parts, the first of which provides for matching the parameters of CTP, and the second — economic-mathematical modeling of this process.

4.2. Matching cargo transshipment process parameters. This part of the problem of ensuring the coordinated GTH management to a great extent corresponds to the contents of the initial stage of justifying the parameters of the single operation process of the transport hub (SOPTH), especially such as the number and location of production zones to perform operations with railway rolling stock, specialization and re-resourcing of these zones, car spotting/picking modes, regulatory time for car-handling in production zones, etc.

As shown in the above-mentioned theories [14, 15], a necessary and sufficient condition for achieving coordination in joint actions of any individuals is their interest in the end results of joint activity that occurs due to the establishing *agreement* between the partners. In general, the agreement between two or more subjects is achieved by the following universal diagram, given below in the Fig. 1.

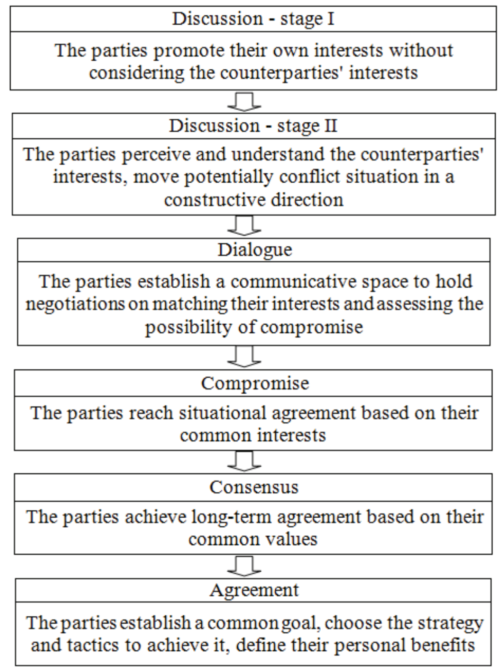

Fig. 1. Diagram of reaching agreement between the interacting subjects

All stages play an important role in ensuring the effective implementation of the above diagram of constructing the agreement between the interacting subjects. Herewith, the overall result of subjects interaction is to a great extent affected by the discussion and dialogue stages, the substantive content of which ultimately influences reaching the agreement. Obviously, the discussion can lead to positive results in only one case, namely, when it is based on tolerance of subjects and their real interest in achieving mutually acceptable results of their joint activities, which is found during the dialogue.

There are different interpretations of the concept of dialogue and explanations of its phenomenal nature. Thus, in the social management theory, it is noted that the dialogue produces a certain emotional «event», leading to the psychological unity of the subjects, in which «...the creative process of inter-opening and inter-development takes place, the conditions for self-action and self-development are created» [15]. At the same time, it is stressed that meaningful dialogue is possible when meeting the following conditions: absence of prejudice between the counterparties, their equality and willingness to certain self-restrictions, mutual trust and understanding.

In case of a positive conclusion of the dialogue, its participants confirm their commitment to recognize the right of each other to the desire to achieve their own benefit and at the same time to strengthen their willingness to make concessions for the sake of taking common business decisions. Eventually, the possibility of proceeding towards searching for a compromise (and similarly consensus) becomes real.

Let's consider the corresponding procedure on the example of reaching a compromise between the main GTH subjects — ports and port railway stations — in determining one of the varieties of the SOPTH parameters — namely, time standards for car handling in the port. In this case we will take into account that solving this problem, ports and stations will act as competitors, the rivalry of which takes place around the indicator of normative time for car spotting handling at the port cargo fronts.

It is obvious that reducing this time is definitely advantageous for stations since this results in decreasing the total time of cars stay in the GTH and, thereby, increasing their carrying capacity, which is beneficial for the company-owner of the car fleet. And this allows the station to raise tariffs for car handling. At the same time, this approach is associated with need to improve the mechanization level of cargo fronts, which requires adequate funding and, therefore, a logical increase in tariffs for car handling. But such a prospect is undesirable for ports since it may lead to loss of traffic volumes.

From the above explanations it follows that the time standards of SOPTH should be of compromise nature, that is to be established by resolving the conflict situation, in which there is a clash of the business interests of ports and stations.

As it is known, the methodological arsenal of the game theory is commonly used for studying such conflicts. With this approach, in the particular considered GTH, the port and station should be treated as players, variants of their business conduct — as strategies, common strategies (common solutions) — as the outcomes of the game, and the benefit, reached by players — as a winning of each other.

Let D and G be the sets of strategies of the port and the station respectively. Let them choose strategies $x \in D$ and $z \in G$, which leads to the outcome of the game (x, z). Herewith, winnings of port $f(x, z)$ and station $g(x, z)$, which depend on both each player's own strategy, and the strategy, chosen by the contractor. Obviously, the objective of each player is to maximize his winning function, respectively — $f(x, z)$ and $g(x, z)$ using the chosen strategy.

Let's note that, proceeding to setting the compromise levels of SOPTH standards (i. e., before the debate stage), the port and the station act as players with conflicting interests and can refrain from mutual informing. Under this condition, antagonistic game may develop between them, in which players have to make their choices simultaneously, not knowing about the choice of each other. Therefore, the port and the station have to choose strategies, targeted at the worst behavior of counterparties, i. e. follow the principle of guaranteed result as maximin payoff for them, that is:

$$\left.\begin{aligned} F_1 &= \max_D \min_G F_1(x,z); \\ F_2 &= \max_G \min_D F_2(x,z). \end{aligned}\right\} \qquad (1)$$

At the same time, at the end of discussion and dialogue stages, when it becomes possible to find a compromise, competitive confrontation between interacting subjects almost completely loses the conflict sharpness, still each subject keeps the desire to maximize his own benefit, but without prejudice to the counterparty (counterparties). Under this condition, the relationships between competing subjects acquire the character of cooperation that allows to treat them in formal terms as a cooperative game in the form of an arbitration award or Nash bargaining problem [16].

When searching for the arbitration award, the set of possible outcomes of the game is studied:

$$\bar{S} = \{(x,z):\ x \in D,\ Z \in G\}, \qquad (2)$$

each being associated with winnings of port and station.

Further, based on the results of a preliminary agreement between the GTH partners, set of possible outcomes $S \in \bar{S}$ is fixed, the set $S \in \bar{S}$ in two-dimensional space of players' winnings is as follows:

$$W = \{(u,v):\ u = f(x,z),\ v = g(x,z),\ (x,z) \in S\}, \qquad (3)$$

and is called the set of admissible arbitration awards.

Basically, both the port, and the station are not required to accept the arbitration award, and then they can rest content with solutions $\bar{u}$ (for the port) $\bar{v}$ (for the station), which are provided for by each subject independently. The point $(\bar{u}, \bar{v})$, corresponding to this solution is called status quo point or change point. Let's note that guaranteed winnings of players, determined by the formulas (1) can be, for example, taken as $\bar{u}$, $\bar{v}$.

The three $(W, \bar{u}, \bar{v})$ is the arbitration task, for which there is an arbitration award (u^*, v^*), where u^*, v^* are winnings of the first and second player respectively. Herewith, the mapping of A, which assigns arbitration award $(u^*, v^*) = A(W, \bar{u}, \bar{v})$ to each arbitration task, is defined as arbitration scheme.

J. Nash has been first to define the arbitration award for the case of two players, which corresponds to our example and substantiated the correctness of its achievement at the validity of system of certain axioms (or assumptions in the terminology of [16]).

The Nash theorem argues that if the set W is convex, closed, bounded and has interior points, then there is an only arbitration mapping of A, satisfying the mentioned axioms. At that, the defined solution:

$$(u^* - \bar{u})(v^* - \bar{v}) = \max_{(u,v) \in W} (u - \bar{u})(v - \bar{v}), \qquad (4)$$

is called the Nash arbitration award.

Thus, the problem of finding the Nash arbitration award consists in maximizing the function $F(u, v) = (u - \bar{u})(v - \bar{v})$ on the set W.

4.3. Cargo transshipment process modeling. It seems clear that the task of finding compromise levels of SOPTH time standards formally fully satisfies the Nash theorem conditions, whereby using the procedure of finding the arbitration award in its studying is justified.

We will consider the task under discussion in the following formulation. Suppose that, for some period of time, divided into r $(k = \overline{1,r})$ segments (e. g., hours), it is necessary to implement CTP by moving certain cargo volumes (e. g., appropriate rail cars, trunk cars, shiploads) by pre-accepted organizational and technological options (OTO) with the passage through specifically fixed production zones within GTH.

Herewith, we consider the zones, equipped at the port railway station (tracks — main, receiving-departure, rip and crossover), in the port (dead-end railway tracks, cargo fronts — cordon, rear, storage) and near the port (transit-freight terminals to service trunk cars) as production zones. Moreover, we agree to consider that the production zones are characterized by carrying capacity and permissible usage time within the control interval, and their quantity can be increased, if necessary, by transferring workers from other facilities, serviced by GTH enterprises.

We will also assume that the effectiveness of CTP implementation is estimated by the rate of ensuring time standards of cargo and transport modes stay in the GTH that meets the interests of customers and, thus, increases the GTH attractiveness (competitiveness). This fact is equally beneficial to all GTH subjects, whereby it can serve a common purpose for them, and hence, guarantee of agreement.

We proceed to formalizing the discussed problem of and introduce necessary notations, namely: j — cargo traffic code $(j=\overline{1,n})$; i — code of production zones of cargo traffic handling $(i=\overline{1,m})$; k — code of the time period of the planning horizon $(k=\overline{1,r})$; Π_{ijk} — carrying capacity of the i zone during handling the j cargo traffic during k time interval; T_i — reserve of the working time of the i zone during the planning interval; T_{ik} — reserve of working time of i zone during the k time interval; C_{jk} — numerical estimate of j cargo traffic handling priority during the k time interval; X_{ijk} and $\bar{X}_{ijk}$ — minimum and maximum volumes of the j cargo traffic respectively that must be handled during the k time interval; Y_{ijk} and $\bar{Y}_{ijk}$ — minimum and maximum permissible usage time of i zone, respectively, for the CTP implementation during the k time interval; Z_{ijk} and $\bar{Z}_{ijk}$ — minimum and maximum permissible usage time of i additional zone during the k time interval, respectively.

Let us take the following indicators as model management parameters: X_{ijk} — transshipment volume of j cargo traffic in the i zone during the k time interval; Y_{ijk} — usage time of the i zone for the transshipment of the j cargo traffic during the k time interval; Z_{ijk} — usage time of the i additional zone for the transshipment of the j cargo traffic during the k time interval.

We assume that the CTP implementation effectiveness is estimated by the level of compliance with the passage terms of cargo traffics together with the transport modes through the production zones, thus, the absolute efficiency maximum is achieved at strict observance of the SOPTH norms.

In the above notations, the desired model of the CTP optimization problem is as follows:

$$F=\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r}C_{jk}X_{ijk}+\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r}A_{jk}Y_{ijk}+$$
$$+\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{r}D_{jk}Z_{ijk}\ -\ \max(\min); \qquad (5)$$

$$\sum_{j=1}^{n}\sum_{k=1}^{r}\frac{1}{\Pi_{ijk}}X_{ijk}\le T_i;\ i=\overline{1,m}; \qquad (6)$$

$$\sum_{j=1}^{n}(Y_{ijk}+Z_{ijk})\le T_{ik},\ i=\overline{1,m};\ k=\overline{1,r}; \qquad (7)$$

$$\underline{X}_{ijk}\le X_{ijk}\le \bar{X}_{ijk},\ i=\overline{1,m};\ j=\overline{1,m};\ k=\overline{1,r}; \qquad (8)$$

$$\underline{Y}_{ijk}\le Y_{ijk}\le \bar{Y}_{ijk},\ i=\overline{1,m};\ j=\overline{1,m};\ k=\overline{1,r}; \qquad (9)$$

$$\underline{Z}_{ijk}\le Z_{ijk}\le \bar{Z}_{ijk},\ i=\overline{1,m};\ j=\overline{1,m};\ k=\overline{1,r}. \qquad (10)$$

Terms of the given model have the following substantial sense:

- ensuring an optimal way of CTP implementation in terms of observing normative terms of cargo and transport modes handling (5);
- limitation of using the working time reserve of the i zone during the planning interval (6);
- limitation of ensuring the total usage time of primary and secondary production zones within the working time reserve during time periods for the CTP implementation (7);
- compliance of transshipment volumes and parameters of industrial zones with specified limits of their change (8)–(10).

It should be noted that the optimal solution of the problem (5)–(10) is ensured by introducing the estimates C_{jk}, A_{jk}, D_{jk} as variable coefficients with the unknowns into objective function (5). Herewith, these coefficients must be set in ascending or descending order from the beginning to the end of each time period when solving the problem on the max or min of the functional F respectively.

5. Approbation of research results

The above characterized approaches to ensuring the coordinated GTH management and CTP optimization were presented at international scientific conferences, as well as scientific and technical conferences of the Odessa National Maritime University (2013–2014) and in both cases were approved. At the same time, they were taken as the basis for the relevant techniques that have been developed and tested by the author through implementing a series of experimental calculations using real data of Odessa and Belgorod-Dniester transport hubs. The results obtained confirm the theoretical consistency of techniques, their technological effectiveness and practical usefulness.

When performing experiments, it was revealed that practitioners of ports and port railway stations, belonging to the above mentioned GTH are not quite psychologically ready to hold the procedure of coordinating joint actions in the CTP management at the stages of working out the compromise and consensus regarding overcoming the corporate egoism. However, at the final stage of the experiments most of the production workers have agreed that the marked psychological barrier is surmountable if there is, as they say, good will.

At the same time, employees of both groups of related GTH enterprises have unhesitatingly recognized the correctness of the orientation of solving the CTP optimization problem to ensuring minimal deviations in the estimated passage time of cargo traffics and transport modes through GTH from positions, provided by SOPTH.

6. Conclusions

Summarizing the review of characterized results of studying the problem of ensuring coordinated CTP management in GTH, it can be concluded that the purpose and objectives of the next stage of its study are naturally associated with the methodological layout of the proposed implementation mechanism, the above described scheme of achieving the agreement among interacting in GTH industrial enterprises and service structures with further CTP optimization. Currently (since June 2014), the author of this paper together with specialists of Odessa, Ilyichyovsk and Belgorod-Dniester ports, their port railway stations and Odessa railway administration deals with creating a package of appropriate organizational and methodological materials.

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ОБЕСПЕЧЕНИЕ СОГЛАСОВАННОГО УПРАВЛЕНИЯ ПРОЦЕССОМ ПЕРЕВАЛКИ ГРУЗОВ В ОБЩЕТРАНСПОРТНЫХ УЗЛАХ

В статье предложен оригинальный подход к обеспечению согласованного управления транспортными узлами, основанный на сочетании методологии классической науки оптимального управления и конструктивных идей прогрессирующих в настоящее время новых концепций делового поведения и социального управления. При этом установлено, что реализацию предлагаемого подхода необходимо осуществлять в два этапа: вначале необходимо согласовать параметры процесса перевалки грузов, а затем обеспечить осуществление этого процесса в оптимальном режиме.

Ключевые слова: транспортный узел, перевалка грузов, оптимальное управление, партнерское взаимодействие, оптимизация грузоперевалки.

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УДК 621.318

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РАСЧЕТ ДВУХЧАСТОТНЫХ ИНДУКТОРНЫХ СИСТЕМ — ИНСТРУМЕНТОВ ВНЕШНЕЙ МАГНИТНО-ИМПУЛЬСНОЙ РИХТОВКИ АВТОМОБИЛЬНЫХ КУЗОВОВ

В статье проведен расчет инструмента внешней магнитно-импульсной рихтовки кузовных элементов автомобилей. Получены основные аналитические зависимости для расчета напряженностей электрических и магнитных полей, возбуждаемых с помощью рассматриваемой двухчастотной индукторной системы. Достоверность полученных результатов подтверждена проведенными предельными переходами к известным классическим закономерностям.

Ключевые слова: *магнитно-импульсная обработка металлов, индукторная система, инструмент рихтовки, магнитно-импульсная рихтовка, автомобильные кузова.*

1. Введение

Разработки технических систем для выравнивания заданных участков на поверхности тонкостенных листовых металлов инициированы, в первую очередь, спросом на выполнение операций по реставрации кузовных покрытий автомобилей и корпусов самолетов. Причем, как показывает практика, до 80 % повреждений приходится на небольшие и средние повреждения. Половина из них — это вмятины, не требующие замены