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*Проведеними дослідженнями в організації взаємодії різних видів транспорту на інтермодальних терміналах встановлено, що для досягнення ефективного функціонування перевантажувальних терміналів необхідним є удосконалення технологічного процесу роботи терміналу. Зокрема, за умови задоволення основних вимог – безперервність, ритмічність, паралельність та поточність усіх операцій, максимальне суміщення при високій якості безумовного використання. Доведено, що досягнення відповідних умов можливе при використанні дескриптивної моделі двоportalного терміналу, функціонування якого забезпечується процесами самосинхронізації руху автоматизованих платформ, здійснюючих перевезення контейнерів між автомобільним та залізничним порталами.*

*Встановлено, що створення досконалих комп'ютерних моделей для потреб організації взаємодії різних видів транспорту на інтермодальних терміналах як проектно-конструкторську задачу треба вирішувати у поєднанні дескриптивних та аналітичних моделей. В даних моделях виділяються програмні та апаратні компоненти, забезпечуючі умови здійснення концепції самосинхронізації руху навантажувачів. Зокрема встановлено, що самосинхронний підхід управління забезпечує велику ступінь узгодження при функціонуванні контейнерного терміналу та дозволяє збільшити паралельність процесів, тобто одночасне здійснення подій у системі.*

*Показана можливість формалізації процесів самосинхронізації засобами мереж Петрі. Цей математичний апарат дуже зручний для моделювання динамічних дискретних систем та дозволяє дослідити послідовне виконання всіх процесів, що відбуваються на інтермодальному терміналі. На основі моделювання доведено, що середній простій контейнера на терміналі зменшується, що дозволяє збільшити переробку спроможність та зменшити питомі витрати на переробку контейнера на терміналі.*

*Таким чином, є підстави стверджувати, що цілком можливою є розробка технологічно завершених термінальних структур "морський порт – залізничний портал – автомобільний портал" у різних конфігураціях. Тип конфігурації залежить від обраних логістичних маршрутів доставки вантажів, застосувавши для цього наведену методику організації роботи двоportalного терміналу*

*Ключові слова: самосинхронізація, мережа Петрі, інтермодальні перевезення, контейнерний термінал*

UDC 656.073.25(477)

DOI: 10.15587/1729-4061.2018.151929

## STUDY INTO CONDITIONS FOR THE INTERACTION BETWEEN DIFFERENT TYPES OF TRANSPORT AT INTERMODAL TERMINALS

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### 1. Introduction

The most important direction of the transport policy of countries in the context of the globalization of international relations is the search for an optimal combination of conditions for functioning of the main international transport corridors. The development of a national network of international transport corridors, which are parts of the Crete in-

ternational transport corridors and which correspond to the norms and standards of the European Union, provide conditions for attraction of additional volumes of transportation. The XXI century challenges the development of relations in the field of continental transport in the new Europe-Asia format. The main modern trend in the world transport system is the development of mixed freight transportation. International practice suggests that two thirds of international

freight transportations related to “door-to-door” combined interconnections in recent years. Combined traffic obtained recognition both in international and domestic traffic, because combined traffic gives a freight owner a number of advantages that are the most effective combination of several modes of transport. Combined transportations (intermodal transportation) provide an opportunity to optimize terms of transportation, to reduce the costs of storage and transportation of freight [1, 2].

Important conditions for development were the space and time of moving of things, people, and information. The zones of intensive production were the USA, Western Europe, Japan, and the USSR from the middle of the twentieth century. From the 90s (after the collapse of the USSR), China, South-East Asia, India, and Latin America joined them.

These new systems are huge. Thus, a huge “potential difference” raised and it grows – Asia is in dire need of fast trade channels with Western Europe. According to the forecasts from the International Monetary Fund, the trade between Asia and Europe will amount to almost a trillion dollars next year. Transport intercontinental systems acquire an increasing strategic importance in geopolitics under these conditions.

Currently, the main transport flows from Southeast Asia to Europe go through the Suez Canal. But its throughput capacity is exhausted. It is possible to provide the growing trade turnover only with new land corridors, using such types of connections, as multimodal and intermodal transportation [3, 4].

An important role in coordination of operation of different types of transport is rational distribution of volumes of transported freights, including switching of a share of volumes of freights from one type of transport to another. Important elements in the interaction of different types of transport are terminals, which carry a large amount of transshipment operations. Inefficient interaction of different types of transport at terminals reduces efficiency of intermodal transport development and operation productivity, it increases cost of transportation and delivery time of freights.

Therefore, it is important to study conditions of interaction between different types of transport at intermodal terminals under such conditions. This renders relevance to the subject of this research.

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## 2. Literature review and problem statement

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The attention of scientists to the development of multimodal systems and intermodal transport technologies for delivery of goods is increasing steadily, due to numerous advantages of such a method of transportation [5]. The conducted study indicate that a base for creation of an intermodal transport system should be freight transport-and-distribution and terminal complexes constructed at connection places of different types of transport. Therefore, scientists pay great attention to the study of conditions of the functioning of terminal complexes.

Proceeding from the above, authors of paper [6] explore problems of intermodal freight traffic from the point of view of the system and management using the proposed model of intermodal freight transport networks. The relevant model takes into account time intervals of the arrival of containers to a terminal. This study considers the problem of intermodal planning of freight traffic in terminal complexes is

considered separately for each type of transport. However, we should note that this paper does not give conditions for the interaction of different types of transport in this paper. The authors of work [7] considered conditions for the operation of intermodal transport, based on cost analysis, taking into consideration technical and operational parameters [7]. Their model describes the conditions for the transportation of goods, taking into consideration costs at all stages of the transport process. The purpose of the study was to determine how to redistribute freight traffic between terminal systems efficiently. It describes efficiency of transportation of freights by different types of transport, as well as conditions for efficient transshipping of freights at different terminal complexes. The paper proposes the topology of location of intermodal terminals and conditions for their effective operation. But it does not consider the modern operation of an intermodal terminal itself in the course of freight operations. Paper [8] presents a detailed analysis of application of simulation models in development of terminal complexes and carries out simulation of terminal’s operation with the interaction of different types of transport. But the relevant study does not take into consideration conditions of operation of intermodal terminals, taking into consideration vehicles, which handle transshipping of freights.

The authors focus on the problems related to the operation of intermodal freight traffic based on flow routing [9, 10]. The studies offer models for optimization of intermodal networks to explore competitiveness of alternative routes for relocation of goods. Intermodal terminals are important elements in these models. The correct functioning of the terminal complex makes it possible to distribute freight flows effectively. Therefore, it is important to improve processes of interaction between different types of transport on intermodal terminals. Studies [11, 12] consider the state of mixed freight transportation in dependence on conditions and specifics of transportation. They also give a legal analysis of the concept of “freight forwarding in direct mixed traffic”. The aim of the studies is formation of the technology of operation of terminal complexes in terms of more coordinated work at transshipping from different types of transport. They offer approaches to optimization of transport flow, which arrive to intermodal terminals. The prospects of sustainable transport development in Europe are associated with the promotion of mixed (intermodal) transport. Therefore, Europeans consider the peculiarities of the functioning of the intermodal freight transport system in more detail in terms of the behavior of organizers of transportation and characteristics of the transport process of freight delivery [13]. Therefore, it is important to resolve issues related to the operation of intermodal terminals, namely the synchronization of processes in performance of freight operations, which are essential in formation of mixed traffic. Based on the above, it is necessary to consider the actual aspects of organization of the interaction of different types of transport at intermodal terminals, which are essential for establishment of the efficient functioning of a terminal.

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## 3. The aim and objectives of the study

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The aim of this study is to increase the efficiency of transshipment and delivery of goods through development of a methodology for the efficient organization of operation of intermodal terminals. The relevant conditions will provide

an opportunity to improve the efficiency of the transport process at organization of intermodal transportation.

We set the following tasks to achieve the objective:

- establishment of features of operation conditions of intermodal terminals in the course of freight operations;
- formation of the technological process of container platform operation with the interaction of different types of transport;
- formalization of the technology of intermodal terminal operation using Petri networks.

#### 4. Materials and methods used in the study

##### 4.1. Special features in the functioning conditions of intermodal terminals that perform freight operations

Intermodal transportation of goods (ITG) has been recognized as a universal scheme of transportation for almost all types of products obtained under modern production conditions. The corresponding scheme is functioning stably and effectively. It is necessary to focus efforts on organization of interaction between different types of transport at ITG transshipment terminals at the stage of its introduction. If all parts of the production process will work smoothly, then the technological process of a terminal will satisfy the basic principles of its operation. The main principles of the operation of a terminal are: continuity, rhythm, parallelism and sequenced-flow of all operations, their maximum combination with high quality unconditional use.

The search for solutions to achieve these requirements should take into consideration a conceptual shift “from functions to processes”, which exists in the methodology of ITG research. This means that a degree of integration of individual functions of technological units reached such an extent that their systemic effect already exceeds the expected effect of the usual additive accumulation of results. Here we are talking about the achievement of a synergistic interaction of a systemic nature, when the processes of self-organization (focus, adaptation, self-preservation, and self-regulation) are dominant in the foreground. That is why it is necessary to look for processes that already exist (or to synthesize new ones) that would satisfy the requirements for improvement of the interaction of different types of transport involved in ITG (continuity, rhythm, parallelism, and sequenced-flow). As we already noted, we need a computer model of container processing, which will determine a nature of the required processes, to improve the technology of a container terminal. If we consider this task in the light of modern information technologies, then we should solve it as a task of hardware support for intellectual systems, which has the concept of self-synchronization among its solutions [14].

##### 4.2. Formation of the technological process of operation of a container platform at the interaction of different types of transport

We create an imaginary descriptive model of an intermodal container terminal to solve the relative task problem. The terminal receives containers delivered by rail at the one side (Z portal) and containers delivered by motor transport at the opposite side (A portal) (Fig. 1).

There are two opposing lanes for transshipment of containers on the territory of the terminal: from Z to A and from A to Z. They provide cyclic movement of goods with the use of forklift trucks. Bridge cranes K1 and K2 perform

transshipment to main rail platforms or car trailers (or one of them) from platforms. Only one forklift truck can stay on the platform. Consequently, we must control their movement to avoid collisions during the arrival (exit) on the crane platform.

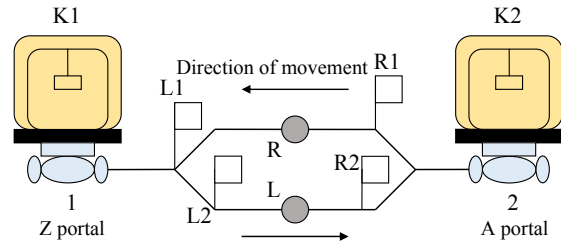


Fig. 1. Descriptive model of the intermodal container terminal

Let us consider the possible technological situation for the management. The forklift 1 is on the site of K1 crane platform and a container is loaded on it and a corresponding signal appears about the completion of this operation. The forklift 2 is on the site of K2 crane platform, where unload of moto transport occurs, and after the installation of a container on it, there is also a signal about the completion of the operation. Next, the forklift moves along the paths marked as vectors of the direction of motion in Fig. 1. There are four traffic lights installed: L1, L2, R1, R2 to avoid collisions of forklifts on one-way access roads to cranes.

Customs control (care) takes place in R, L zones. We can interpret traffic lights as predicates that take values 1 if the path is open and 0 value – if the path is closed. In addition, we introduce other predicates and propositional variables that are necessary for the complete description of the terminal operation:

- $x_1, x_2, x_R, x_L$  variables, which simulate sensors for formation of signals about the presence of forklifts in the corresponding zones of the terminal: 1 is here; 0 is not here;
- $x_1^+, x_1^-, x_2^+, x_2^-$  are signals from the relevant forklift about the completion of loading or unloading;
- $y_0^+, y_0^-, y_1^+, y_1^-$  are signals of the passage of customs control: + – the result is positive, 0 – the result is negative.

##### 4.3. Formalization of the technology of intermodal terminal operation using Petri networks

We propose to use the mathematical apparatus of Petri networks to solve the problem. This mathematical device is very convenient for simulation of dynamic discrete systems. Base Petri network consists of positions, transitions, arcs, and tokens. The positions simulate conditions and the presence of a token on the corresponding position indicates fulfillment of the condition. The transition in Petri network simulates an event, that is, an action that occurs in the system. The occurrence of an event corresponds to the operation (or launch) of the transition.

Positions and transitions between them represent the “condition-event” causal relationship in Petri networks. And it is possible to present a certain state of the system or an operation that is performed with the object (a carriage, a container) in the form of a position. Since transitions from one state to another state are directed, we can say that the graph of Petri’s networks is a two-tone directed multigraph [15, 16].

The arches interconnect positions and transitions. Fig. 2 shows Petri Networks with 4 positions and 2 transitions.

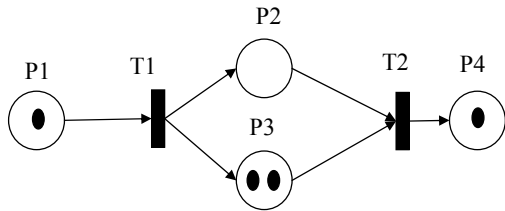


Fig. 2. Petri Networks with 4 positions and 2 transitions

We can present Petri network as the corresponding set

$$N = (P, T, G, \Omega), \tag{1}$$

where  $P$  is the set of all positions;  $T$  is the set of transitions;  $G$  is the set of arcs of a network;  $\Omega$  is the set of arcs weights.

Thus, we can use Petri Networks to simulate the process of transshipment of a container from one type of transport to another one in order to analyze states of the system and transitions between them. This apparatus makes it possible to investigate the consistent execution of all processes occurring on the intermodal terminal. We formalize technological process  $P, i=1,2$  of motion of the  $i$ -th platform using graphic tools of Petri network (Fig. 3).

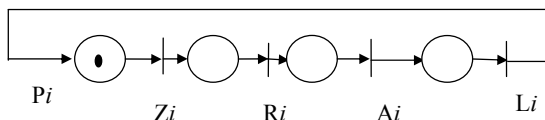


Fig. 3. Formalization of the technological process by Petri network graph for one platform

This process is consistent and it includes  $Z_i$  cycles – unloading of a container from the railroad transport,  $R_i, L_i$  – passages of customs control zones,  $A_i$  – loading of a container to the road transport (these symbols denote Petri network transitions). The presence of a marker at the input (initial) position of the transition represents the forklift movement from the previous (given) point in the current (next) item. We interpret the fact of actuation of  $Z, R, A, L$  as the completion of loading, passing of  $R$  zone, completion of unloading, passage of  $L$  zone, respectively. Fig. 4 shows the general model of the synchronization of  $P_1$  and  $P_2$  processes of forklift movement in both directions, for which the initial states are  $Z^1$  and  $A^2$ .

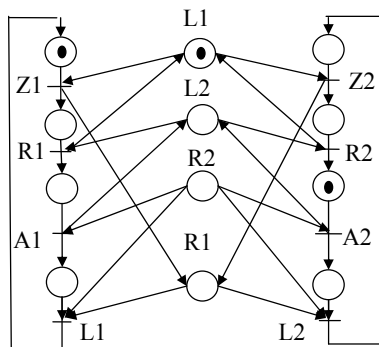


Fig. 4. Formalization of the technological process by Petri network graph for two platforms

The synchronization occurs due to the positions marked with  $L1, L2, R1, R2$  symbols, and the mechanism of its im-

plementation is equivalent to the use of E. Dijkstra traffic lights [16]. Analysis of this Petri network shows that it is active, safe, and stable in operation (it is impossible to excite the same name transitions simultaneously, that is, crossing the routes in any point (zone) of the path).

We should also note that there is strict synchronization in this version. The departure of a forklift from the given  $Z, R, A, L$  point is possible if only the other forklift is ready for departure to diametrically located to them  $A, L, Z, R$  points, respectively. However, technological situations can be different both in terms of duration of operations, and in terms of the state of equipment and mechanisms, which will require changes in the order of forklift movement in one way or another.

Fig. 5 shows one of the examples of a change in the order of departure: the departure of one forklift from the given  $Z, R, A, L$  point is possible after departure of the other forklift in the direction to the next  $A, L, Z, R$  point.

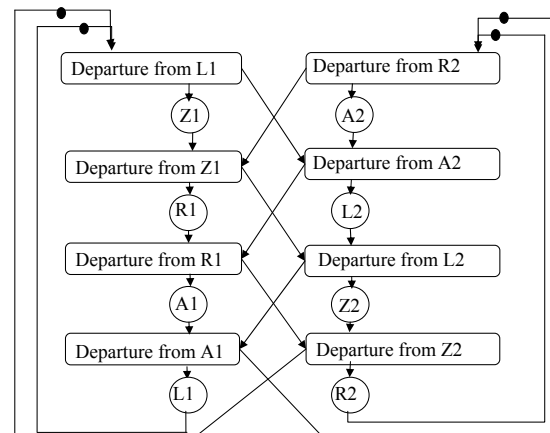


Fig. 5. Marked graph for situations of departure changes

Then it is necessary to follow the standard procedure for the synthesis of a signal graph in accordance with Petri network in Fig. 4, and to construct excitation functions for paraphase implementation of RS-triggers on its basis. In this case, with reference to [15], we need about 20 such triggers for construction of the appropriate controller for the general control system.

We should note that the modern technology of reconfigurable computing based on programmable logic integrated circuits (PLIC) [17] makes it possible to create much more complex computer architectures. Logical integrated circuits should provide such functional properties as resiliency, adaptability and collaboration of computing and network systems. Therefore, it is quite possible to develop technologically completed “seaport – railroad portal – automobile portal” terminal structures in different configurations in dependence on selected logistics routes.

### 5. Results of studying the conditions of operation of the intermodal terminal

We obtain relevant indicators that give possibility to make a conclusion about the efficiency of operation of the container terminal in the simulation of the terminal’s operation.

Fig. 6 shows construction of Petri network for a module of the container terminal serviced by cranes. The crane performs three variants of the technological cycle:

- unloading a loaded container to a platform and returning empty run of a crane to a carriage;
- loading a loaded container from a platform to a car and returning empty run to a former position;
- direct transshipment of a loaded container from a platform to a car and return empty run of a crane to an initial position.

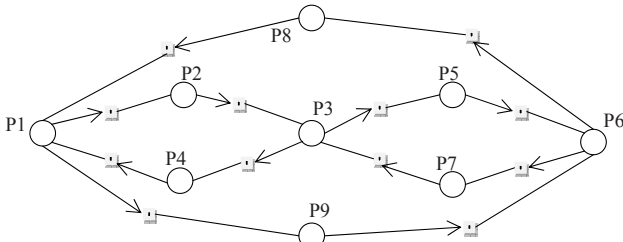


Fig. 6. Petri Networks for the module of the container terminal

Positions of the crane  $p_i$  and transition positions  $t_{ij}$  are as follows:

- $p_1, p_6$  – position of the crane, respectively, near a carriage and a car during unloading or loading of a loaded container;
- $p_2, p_4$  – positions that simulate time of movement of a crane from a carriage to a storage zone of a loaded crane and selected direction of empty run in the opposite direction;
- $p_3$  – position of a crane in a storage zone at the take-or-return of a container;
- $p_5, p_7$  – positions that simulate time of movement of a crane with a container from a storage zone to a car and empty run in the opposite direction;
- $p_8, p_9$  – positions that simulate time of movement of a crane with a container from a carriage to a car and empty run in the opposite direction;

- $t_{12}, t_{23}$  – positions of the transition from  $p_1$  to  $p_3$ ;
- $t_{34}, t_{41}$  – positions of the transition from  $p_3$  to  $p_4$ ;
- $t_{35}, t_{56}$  – positions of the transition from  $p_3$  to  $p_6$ ;
- $t_{67}, t_{73}$  – positions of the transition from  $p_6$  to  $p_3$ ;
- $t_{18}, t_{16}$  – position of the transition from  $p_1$  to  $p_6$ ;
- $t_{69}, t_{91}$  – positions of the transition from  $p_6$  to  $p_1$ .

Fig. 7 shows a fragment of the interface model to study the operation of the intermodal terminal.

Fig. 8 shows the dependences of calculation time and acceleration achieved during implementation of Petri network.

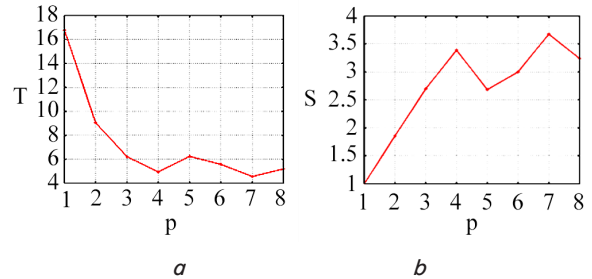


Fig. 8. Dependence of  $T$  time and  $S$  acceleration  $S$  on  $p$  number of processes at a fixed size of Petri network:  
 a – dependence of time on a number of processes;  
 b – dependence of acceleration on a number of processes

We propose to perform verification with the agreement criterion to check the model in the study. The verification by  $\chi^2$  Pearson criterion of the agreement confirms the hypothesis of distribution of deviations according to the normal law. Table 1 shows the output data of the existing model and calculations of model parameters.

Fig. 9 shows a histogram of the distribution of deviations of field observations and simulation results.

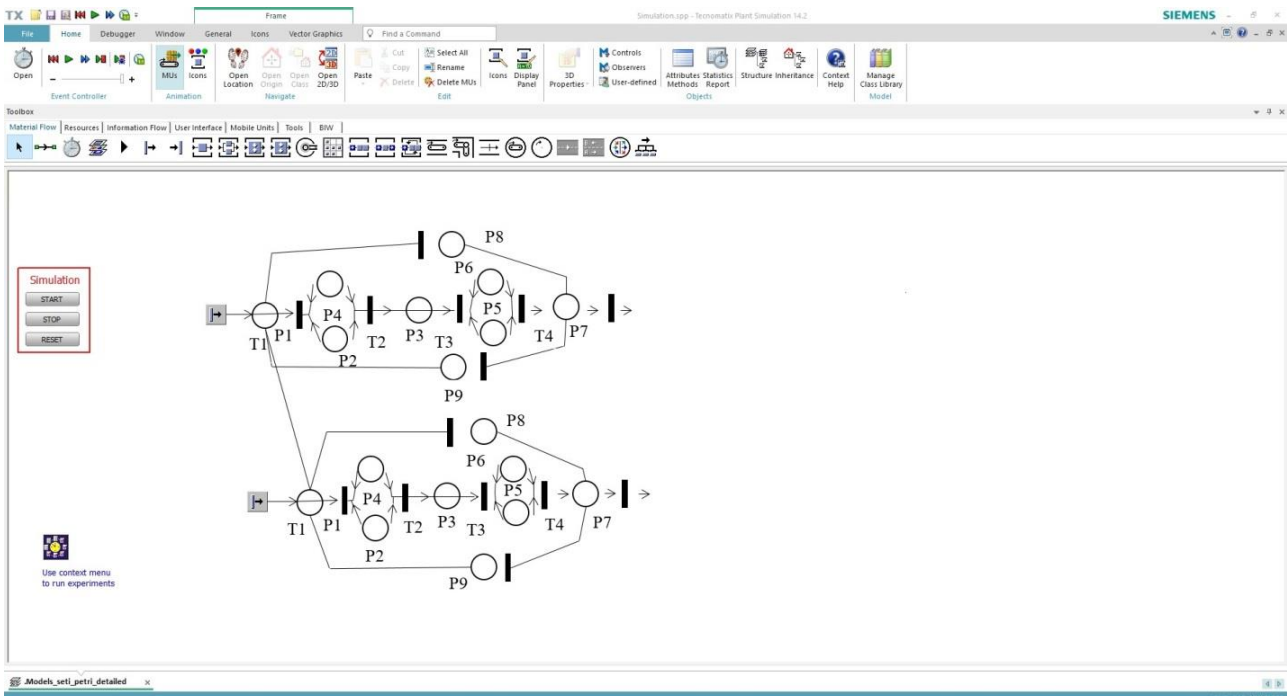


Fig. 7. Fragment of the interface model of the study on the operation of the intermodal terminal

Table 1

Output data and calculations of model parameters

Observation order number	CTS «Liski»	
	Time for relocation of a container, min	
	Result of observation	Result of simulation
1	14.5	14.2
2	16.0	15.4
3	17.1	16.6
4	12.7	12.5
5	13.8	13.3
6	19.8	19.5
7	21.2	20.5
8	16.4	16.0
9	18.3	18.1
10	17.6	17.5
11	12.3	12.1
12	14.5	14.4
13	19.2	18.8
14	20.2	19.5
15	20.8	20.6
16	18.3	18.0
17	16.3	16.0
18	17.8	17.2
19	18.0	17.5
20	12.5	12.1
21	13.8	13.4
22	16.7	16.5
23	17.2	17.0
24	18.4	17.9
25	20.5	19.7
26	21.3	22.8
27	20.5	20.3
28	12.5	12.2
29	16.3	16.0
30	17.5	17.3

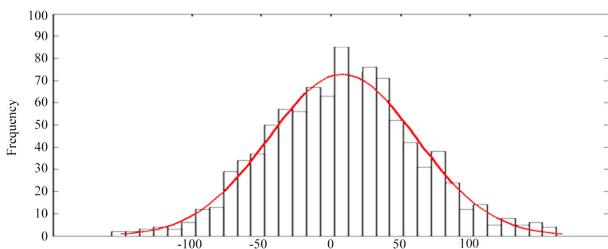


Fig. 9. Histogram of the distribution of deviations of field observations and simulation results

Fig. 10–12 show the comparative analysis of the operation of the container terminal under the existing model of management and the model proposed in this study.

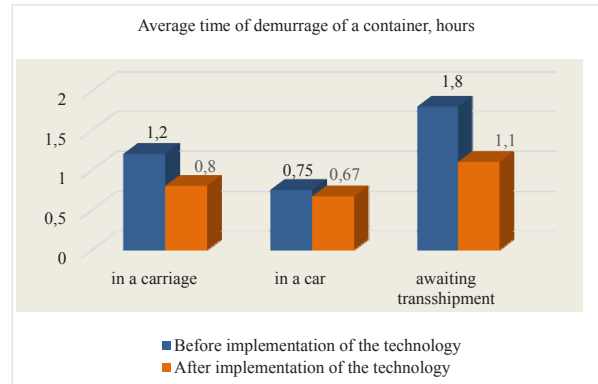


Fig. 10. Average time of demurrage of a container at a terminal

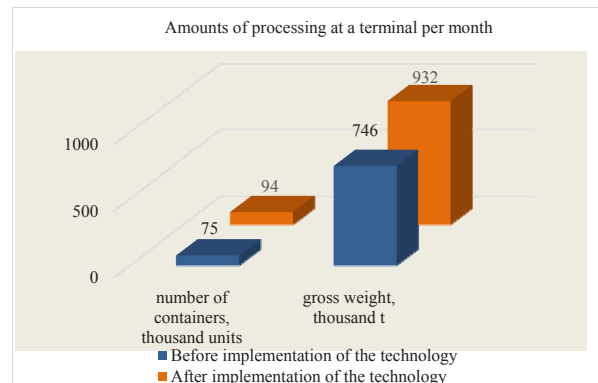


Fig. 11. Dimensions of container handling per month at a terminal

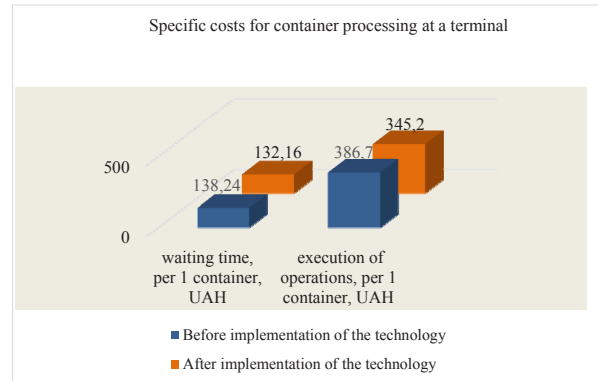


Fig. 12. Specific costs for container processing at a terminal

We identified the main factors, which affect the operation of a terminal, in the study on the operation of the intermodal terminal carried out on a model developed on the basis of Petri Networks. Organization determines unproductive time expenditures by motor transport on the intermodal terminal through registration of transport documentation, unevenness and intensity of arrival of vehicles. The use of the developed model makes it possible to optimize operation of an intermodal terminal.

### 6. Discussion of results of studying conditions for operation of an intermodal terminal

The prospect of intermodal transportation development depends on the possibility to provide high delivery speeds with respect to the mode of operation and rest of drivers of motor vehicles. It also meets the ecological requirements of

motor vehicles in different countries and reduces the cost of transportation, which will increase competitiveness of national carriers. All these factors provide opportunity to integrate the national transport system into the European one gradually. Along with the mentioned factors, the prospect of intermodal transportation in the coming years will depend on development of a network of international transport corridors. Their creation is the priority direction for the international transport complex. Proceeding from this, it is necessary to consider intermodal terminals with great attention.

The main advantage in organization of operation of an intermodal terminal built according to a mathematical model based on Petri networks is a great degree of coherence. This property makes it possible to increase efficiency at interaction of different types of transport. Specifically, if we analyze costs associated with expectations of a container of the corresponding action and costs of operations completion, they decrease, which is a very positive indicator in terms of the efficiency of a terminal. The proposed model provides an opportunity to reduce average time of demurrage of a container and, therefore, increases a number of recycled containers at a terminal.

Consequently, we can state that it is possible to implement the appropriate management model at all intermodal terminals. But the main factor in implementation is the analysis of conditions of operation of different terminal complexes, as each complex has its own technological process. All these factors confirm the efficiency of the operation of the intermodal

terminal in the proposed model of management once again. The developed model for the management at an intermodal terminal makes it possible to establish the relationship between intensity of arrival of vehicles and to estimate time expenditures for performance of individual operations.

## 7. Conclusions

1. Effective interaction of different types of transport at terminals of intermodal transportation of goods is possible if we provide the technological synchronization of loading/unloading operations. This will help to avoid forced stops of crane mechanisms and trucks for transportation of containers.

2. We must solve a design task on creating a perfect computer models for needs of the organization of interaction of different types of transport at intermodal terminals by combination of descriptive model and analytical model. Selection of software and hardware components that provide conditions for implementation of the concept of self-synchronization of movement of forklifts is also important.

3. We should study possibilities of using technologies of reconfigurable computing to create flexible (adaptive) architectures of the logical-and-functional basis of control systems for operation of terminals in further studies on the problems of the organization of various types of transport at intermodal terminals.

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