# MODEL OF MULTIMODAL TRANSPORT NODE FUNCTIONING

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***Abstract:*** *To increase the efficiency of transport nodes functioning taking into account the logistics management principles it is necessary to optimize the structure and capacity of transport nodes' production resources, and to develop such a method for calculating of joint schedules for vehicles and freight hubs of the transport node, which takes into account stochastic nature of the parameters of material and informational flows. For solving the problems of optimal management of transport nodes functioning processes it is proposed to use the specific efficiency indicator, which is determined as a ratio of total costs of clients servicing in transport node to the costs of production resources used while servicing. According to the used approach for formalization of the transport node internal processes, development of the simulation model was implemented on the base of object-oriented programming principles. TransportNode.dll class library has been used as basic tool for simulations. The model implemented on the base of the library allows to take into account stochastic nature of demand and probabilistic nature of technological processes in transport nodes. Some results of numeric simulations for the loading area "Amur-Gavan" of Dnipropetrovsk River Port have been described in the paper.*

***Key words:*** *transport node, technological process, logistics management, system approach, mathematical model, efficiency criterion*

## 1. Introduction

Transport nodes are structural elements of logistics chains. They participate in delivery of goods as elements of technological delivery schemes, which are defined as a set of technical, technological, commercial and legal decisions implemented with the involvement of many intermediaries, which aimed at organizing the process of cargo delivery from shipper to consignee (Stock and Lambert, 2000). Logistics management of transport nodes technological processes supposes the use of systematic approach as the main tool. Interactions between subsystems of a transport node as a logistics system should be considered at the level of flows – material and its accompanying information and financial flows.

In recent studies of multimodal transport systems two main directions should be mentioned – solving the problems on macro level and dealing with tasks at micro level (Florez et al., 2011). The most complex macro level problem is the problem of localization of transport hubs in the nodes of a transport network. The ways to solve this problem are proposed in the papers (Li et al., 2013; Zameni and Razmi, 2015; Racunica and Wynter, 2005). At micro level the main tasks are the justification of managerial decisions on servicing of material flows in transport nodes. Models of transport nodes functioning are usually used as the basic tool to solve the problems at micro level. These models are accepted to be developed on the base of systematic approach, which supposes identification of links between components of the research object and the impact of each element on the system efficiency. As the most important recent researches, where the models of transport node functioning were proposed, the papers (Feng-Ling and Zheng-Yi, 2006; Sun and Cheng, 2010; Mahrous, 2012) should be noted. Authors use contemporary mathematical and modeling tools, such as queueing theory methods (Li et al., 2013), method of analytic hierarchy process (Feng-Ling and Zheng-Yi, 2006),

fuzzy logic (Sun and Cheng, 2010), and computer simulations on the base of ArcGIS platform (Mahrous, 2012).

This paper aims to develop theoretical bases to enhance the processes of logistics management in multimodal transport nodes using object-oriented paradigm for modeling of technological processes.

## 2. Research object description

The process of logistics management in transport nodes we propose to describe on the base of a transport node functioning model $M_N$ as a set of following components (Nagornyi et al., 2014):

$$M_N = \left\{ \{X\}, \{Z\}, \{E\}, \{L\}, K_e \right\} \qquad (1)$$

where:

$\{X\}$ – input parameters, which could be changed while making a decision on transport node functioning,

$\{Z\}$ – environmental effects, which cannot be changed while decision making process, but should be taken into account,

$\{E\}$ – elements of a transport node functioning process,

$\{L\}$ – links between the elements of a transport node functioning process,

$K_e$ – efficiency criterion of a transport node functioning.

As controlled input parameters in a model of a transport node functioning, the authors distinguish (Nagornyi et al., 2014):

- numerical characteristics of productive resources: the book value of productive resources, number of mechanisms by their types, amount of workers engaged in servicing of machinery and vehicles, productivity of machinery and vehicles, operational and economic indicators of their use, and others;
- numerical characteristics of managerial influences: duration of servicing process for cargo units at the certain servicing areas of a transport node, rhythm of loading bays, intervals of arrival of cargo units, level of loading mechanisms use, level of mechanization of loading process, etc.

As environmental influences in a model of a transport node functioning above all the characteristics of demand for services of a transport node should be mentioned – the parameters of incoming material flow. Main numerical parameters of incoming material flow are its intensity and power. Intensity is the characteristic of inflow of requests on cargo delivery; and material flow power allows to characterize the requests mean volume. In details an incoming material flow could be described on the base of a model of sequential requests, which is presented in Naumov (2013). As main numerical characteristics of the requests flow the parameters of the set of stochastic variables are considered: cargo delivery volume, delivery distance, interval of requests inflow. All the input parameters, the system elements and the result of its functioning should be described only with such parameters, which could characterize them numerically.

Links between elements of the transport node functioning process in its model are described with functional dependencies or algorithms. Presence of the dependence indicates the presence of the link and vice versa. A set of links $\{L\}$ contains four subsets:

- links between input factors and system elements ($L_{XE}$): functional dependencies or algorithms, which allows to describe numerically influence of input factors on characteristics of subprocesses of material flow handling in a transport node;
- links between input parameters, which describe influence of environment, and system elements ($L_{ZE}$): functional dependencies or algorithms, which allows to describe numerically influence of environmental effects on characteristics of technological processes in a transport node;
- links between the system elements ($L_{EE}$): functional dependencies or algorithms, which allows to describe numerically the mutual influence of the transport node elements;
- links between system elements and indicators reflecting the efficiency of its functioning ($L_{EY}$): functional dependencies or algorithms, which to describe numerically influence of characteristics of systems elements on the overall result of its functioning.

For solving the problems of optimization of structure and capacity of production facilities for transport nodes as macrologistics systems it's proposed to use the specific efficiency criterion $K_e$, which is defined as a ratio of total expenses $E_\Sigma$ on customers servicing in a transport node to the costs of production resources $C_R$ involved in the service process (Nagornyi et al., 2014):

$$K_e = \frac{E_\Sigma}{C_R} \qquad (2)$$

The proposed efficiency criterion is a dimensionless parameter that indicates the amount of servicing expenses per a production resources cost. This criterion includes an indicator (total expenses on the process of servicing) generally accepted in a practice of logistics management, but also allows to consider the internal system characteristic (cost of production resources).

## 3. Formulation of problems for logistics management in transport nodes

Taking into account the proposed criterion, increase of efficiency of a transport node functioning process supposes decrease of the criterion value for the proposed variant of servicing process in comparison to existing (basic) variant of technological process. In other words, task of a transport node servicing process improvement is considered to be implemented, if such input parameters could be defined, that the following condition is fulfilled:

$$K_e\left(R_X'', M_X'', D_Z\right) < K_e\left(R_X', M_X', D_Z\right) \qquad (3)$$

where:

$R_X''$ and $M_X''$ – numeric characteristics of production resources and organizational impacts accordingly for the improved variant of a transport node servicing process,

$R_X'$ and $M_X'$ – numeric characteristics of production resources and organizational impacts accordingly for the basic variant of a transport node servicing process,

$D_Z$ – numeric characteristics of demand for services of a transport node.

Here, as a working hypothesis the following statement could be used: there such values of input parameters $R_X$ and $M_X$ exist, which for the known demand parameters $D_Z$ ensure the minimum value of the efficiency criterion. To verify the working hypothesis it is necessary to determine the functional dependence $K_e = f\left(R_X, M_X, D_Z\right)$. If the working hypothesis is not rejected, the task of improvement of logistics management in a transport node could be defined as an optimization problem (minimization of the objective function):

$$K_e\left(R_X, M_X, D_Z\right) \to \min \qquad (4)$$

As basic subsystems of a servicing process in a transport node the following subprocesses should be distinguished:

$E_1$ – handling of an incoming material flow at the loading bay with unloading of shipments to the warehouse of a transport node; these operations are implemented at the loading bays of "transport – warehouse" (TW) type;

$E_2$ – intermediate storage of cargo in warehouses of a transport node;

$E_3$ – handling of an outgoing material flow at the loading bay with loading of vehicles from the warehouse of a transport node; these operations are implemented at the loading bays of "warehouse – transport" (WT) type;

$E_4$ – handling of incoming and outgoing material flows at the loading bay with direct transshipment from a vehicle of one transport mode to a vehicle of another transport mode; these operations are implemented at the loading bays of "transport – transport" (TT) type.

Depending on the taken variant of handling of incoming and outgoing material flows, three variants of technological process of requests servicing in a transport node could be distinguished:

- variant of service with transshipments through the warehouse: loaded vehicles, coming to the transport node, are unloaded to the warehouse at the loading bay of TW type; empty vehicles, coming to a transport node, are loaded from the warehouse at the loading bay of WT type;

- variant of service with direct transshipments: loaded vehicles are unloaded at the loading bay of TT type, at the same time loading is implemented for the vehicles, which came to a transport node for loading;

- mixed variant of service: a part of loaded vehicles are serviced at the loading bay of direct transshipments, also a part of vehicles, which came for loading, are serviced at the same time; other vehicles are serviced through the warehouse at the loading bays of TW and WT type.

Demand for services of a transport node we propose to describe on the base of a model of requests flow (Naumov, 2012). It is appropriate to distinguish the flow of requests $D_{Z(in)}$, which forms an incoming material flow in the logistics system of a transport node, and the requests flow $D_{Z(out)}$, which forms outgoing material flow. It should be noted, that

incoming and outgoing material flows are formed as sets of requests on unloading or loading of vehicles of different transport modes. But also widespread is the transport node specialization on performing the operations of loading for vehicles of only one transport mode and the operations of unloading for vehicles of other transport mode: for example, in a transport node could be performed the operations of unloading exclusively for river vessels, and the operations of loading only for rail cars.

To estimate the demand for services of a transport node, it is enough to describe the requests flow with numerical characteristics for requests appearance moments, specific cost of vehicles downtime and volume of a shipment, which should be loaded or unloaded:

$$D_Z = \left\{ \tilde{\omega}, \tilde{\upsilon}, \tilde{\zeta} \right\} \qquad (5)$$

where:

$\tilde{\omega}$ – stochastic variable of the shipment volume, which should be loaded or unloaded in a transport node,

$\tilde{\upsilon}$ – stochastic variable of specific cost of downtime for the vehicle, which arrived to a transport node (depends on vehicle type and its technical and economic characteristics),

$\tilde{\zeta}$ – stochastic variable of time interval between requests in a flow.

Production resources of a transport node, which are engaged in the process of servicing, could be divided on production resources of loading bays $R_X^g$ and production resources of warehouses $R_X^{wh}$.

Loading bay production resources are enough to describe by numerical characteristics of handling capacities and specific cost of service:

$$R_X^g = \left\{ n_g, w_g, \upsilon_g, \upsilon_g' \right\} \qquad (6)$$

where:

$n_g$ – number of handling mechanisms at the loading bay,

$w_g$ – average productivity of a handling mechanism, t/h,

$\upsilon_g$ and $\upsilon_g'$ – specific costs of handling mechanisms functioning while servicing the requests and their downtime respectively, \$/h.

Production resources of warehouses could be described with numerical characteristics of storage space and storage prime cost:

$$R_X^{wh} = \left\{ s_{wh}, \upsilon_{wh}, \upsilon_{wh}' \right\} \qquad (7)$$

where:

$s_{wh}$ – total usable area of a transport node warehouses, which is used for cargo storage, $m^2$,

$\upsilon_{wh}$ – specific cost of cargo storage, \$/(t×h),

$\upsilon_{wh}'$ – specific cost of warehouse operation without cargo stored in it, \$/(m²×h).

For numerical description of $i$-th element $E_i$ of technological process of requests service in a transport node, the process time and cost characteristics would be enough:

$$E_i = \left\{ \tilde{\tau}_i, \tilde{c}_i \right\} \qquad (8)$$

where:

$\tilde{\tau}_i$ – stochastic variable of duration of request service for $i$-th element (for loading bays – loading or unloading operations duration, for warehouses – storage duration of a shipment),

$\tilde{c}_i$ – stochastic variable of cost of request servicing for $i$-th element of technological process.

As characteristics of organizational influences the quantitative characteristics of production resources and numerical parameters, which describe organization of the process of requests flow service, should be attributed:

$$M_X = \left\{ \psi, \left\{ n_g \right\}, s_{wh}, \left\{ T_\tau \right\} \right\} \qquad (9)$$

where:

$\psi$ – variant of technological process of a transport node functioning (with transshipments through the warehouse, direct handling or mixed variant),

$\left\{ n_g \right\}$ – vector, that displays a number of handling mechanisms at the loading bays of a transport node,

$\left\{ T_\tau \right\}$ – schedule of vehicles arrival to a transport node for servicing (moments of time of vehicles arrival).

Formulation of the problems of logistics management in multimodal transport nodes with the use of mentioned above numerical characteristics could be determined as a following set:

- problem of a choice of rational variant of a transport node technological process: for the known demand characteristics $D_{Z(in)}$ and $D_{Z(out)}$ it is necessary to determine such a variant $\psi$, that is characterized with the minimal value of the efficiency criterion $K_e$;
- problem of estimation of the optimal loading bays capacity in a transport node: for the known demand characteristics $D_{Z(in)}$ and $D_{Z(out)}$ it is necessary to estimate such values of the vector $\{n_g\}$ elements, which ensure the minimal value of the efficiency criterion $K_e$;
- problem of estimation of the optimal warehouse capacity: for the known demand characteristics $D_{Z(in)}$ and $D_{Z(out)}$, and for the known capacity $\{n_g\}$ of loading bays it is necessary to determine such value of $s_{wh}$, which ensures the minimal value of the efficiency criterion $K_e$;
- problem of forming the rational variant of schedule of vehicles arrival to a transport node for loading (or unloading): for the known demand characteristics $D_{Z(in)}$ and $D_{Z(out)}$, and for the known capacity $\{n_g\}$ of loading bays and known warehouse capacity $s_{wh}$ it is necessary to determine such a schedule variant $\{T_\tau\}$, which ensures the minimal value of the efficiency criterion $K_e$.

## 4. Formalization of links between elements of a transport node system

Formalization of links is carried out for the known numerical characteristics of input parameters and elements of the system of a transport node. As the links formalization we understand definition of functional dependence between respective numerical characteristics. A set of the system numerical characteristics and respective functional dependencies represents a mathematical model of the system.

Links of the $L_{XE}$ type are the functional dependences between characteristics of the system elements and characteristics of input parameters. In accordance with the proposed formalization approach, for the $i$-th system element the links of this type are the dependencies of $\tilde{\tau}_i$ and $\tilde{c}_i$ parameters from numerical characteristics of production resources and organizational influences.

For the loading bays duration of the request servicing $\tau_g$ is determined as a sum of duration of waiting for the beginning of service and duration of loading or unloading procedure:

$$\tau_g = \tau_w^g + \tau_{l(u)} \qquad (10)$$

where:

$\tau_w^g$ – duration of the vehicle waiting for the beginning of servicing at the loading bay, which is caused by lack of not busied handling mechanisms, h,

$\tau_{l(u)}$ – duration of the vehicle loading or unloading operation at the loading bay, h.

Servicing cost $c_g$ for the loading bay is calculated on the basis of time parameters of servicing process and specific cost parameters, which characterize requests and handling mechanisms.

For vehicles, arrived in a transport node for unloading, the cost of servicing $c_g^p$ at the loading bay is determined in a following way:

$$c_g^p = \tau_g \cdot (\upsilon + \upsilon_\omega) + \tau_{l(u)} \cdot \upsilon_g \qquad (11)$$

where:

$\upsilon$ – specific cost of downtime of an arrived vehicle, \$/h,

$\upsilon_\omega$ – specific cost associated with the withdrawal of funds from circulation, \$/h.

Specific cost, associated with the withdrawal of funds from circulation, is cost characteristics of the request on servicing in a transport node. The most common approach to evaluation of $\upsilon_\omega$ is its calculation based on the annual rate on bank deposit (Bozarth and Handfield, 2006). In this case it is assumed, that the amount of funds, associated with a shipment value, was invested at the bank deposit account. Based on this assumption, the specific cost associated with withdrawal of funds from circulation, are determined by the formula:

$$\upsilon_\omega = \frac{c_t \cdot \omega \cdot \alpha}{100 \cdot 365 \cdot 24} \qquad (12)$$

where:

$c_t$ – cost of 1 ton of cargo for the request, \$/t,

$\alpha$ – average value of the annual rate of bank deposit in the region, %.

For vehicles, arrived in a transport node for loading, the cost of servicing $c_g^l$ at the loading bay is determined according to the following dependence:

$$c_g^l = \tau_g \cdot \upsilon + \tau_{l(u)} \cdot \left( \upsilon_g + \upsilon_\omega \right) \qquad (13)$$

For the direct transshipment loading bay the costs of servicing $c_g^d$ are determined for a couple of requests, taking into account specific costs of the unloaded vehicle downtime and specific costs of vehicle, that arrived to a transport node for loading:

$$c_g^d = \tau_{l(u)} \cdot \left( \upsilon^{(u)} + \upsilon^{(l)} + \upsilon_g \right) + \\ + \tau_w^{(u)} \cdot \upsilon^{(u)} + \tau_w^{(l)} \cdot \upsilon^{(l)} + c_\omega \qquad (14)$$

where:

$\upsilon^{(u)}$ and $\upsilon^{(l)}$ – specific cost of downtime for vehicles, arrived to a transport node for unloading and loading respectively, \$/h,

$\tau_w^{(u)}$ and $\tau_w^{(l)}$ – duration of period, when vehicle waits for the beginning of servicing due to the lack of unoccupied handling mechanism, for the vehicles that arrived to a transport node for unloading and loading respectively, h,

$c_\omega$ – expenses caused by the withdrawal of funds from circulation, which occur while technological operations at the loading bay of a transport node, \$.

For the warehouses of a transport node duration of the request servicing $\tau_{wh}$ is determined as a sum of duration of waiting for the beginning of service in the warehouse and the storage duration:

$$\tau_{wh} = \tau_w^{wh} + \tau_{st} \qquad (15)$$

where:

$\tau_w^{wh}$ – duration of waiting by a vehicle of the beginning of servicing at the loading bay of TW type, which is caused by the lack of space in the warehouse, h,

$\tau_{st}$ – duration of the shipment storage operations in the warehouse, h.

Cost of the request servicing $c_{wh}$ at the warehouse of a transport node is determined similarly on the basis of time parameters of the storage technological process and specific cost parameters that characterize requests and warehouses:

$$c_{wh} = \tau_{st} \cdot \omega \cdot \upsilon_{wh} + \tau_w^{wh} \cdot \upsilon + \left( \tau_{st} + \tau_w^{wh} \right) \cdot \upsilon_\omega \qquad (16)$$

where:

$\upsilon_{wh}$ – specific cost of storage of 1 ton of cargo in the warehouse of a transport node during 1 hour, \$/(t×h).

Links of the $L_{ZE}$ type are described on the basis of functional dependencies between the system elements characteristics and parameters, which reflect influence of environment on the transport node system, – numerical parameters $\omega$, $\upsilon$ and $\zeta$ characterizing demand for services of a transport node.

For the known values of the handling mechanisms productivity $w_g$ at the loading bays of a transport node the link of this parameter, which numerically characterizes production resources, with the characteristics of the elements of servicing process is implemented through the determination on its basis of the loading and unloading operations duration. For the shipment volume $\omega$ as a numerical characteristic of demand, duration of loading (unloading) process is determined as a ratio of the shipment volume to productivity of the handling mechanism:

$$\tau_{l(u)} = \frac{\omega}{w_g} \qquad (17)$$

The influence on numerical characteristics of the requests servicing subprocesses for the other demand parameter – interval between requests arrival $\zeta$, cannot be determined analytically, although the existence of such a functional dependence is apparent.

The ratio of a shipment volume for the requests on servicing in a transport node to the value of interval between the requests determines the intensity $\xi$ of material flow:

$$\xi = \frac{\omega}{\zeta} \qquad (18)$$

For the flow of $N_r$ requests with known characteristics of variables $\omega$ and $\zeta$, actual value of

the intensity $\xi^{(f)}$ is determined in the following way:

$$\xi^{(f)} = \frac{\sum\limits_{i=1}^{N_s} \omega_i}{\sum\limits_{i=1}^{N_s} \zeta_i} \qquad (19)$$

Time indicators of the requests servicing process at loading bays depend on the input parameters – a number of handling mechanisms $n_g$, productivity of mechanisms $w_g$, the available area of warehouses and the schedule $\{T_\tau\}$ of vehicles arrival for servicing in a transport node. A set of mentioned parameters determines an integral characteristic of a loading bay as of a servicing system – the productivity of the bay $w_b$:

$$w_b = f\left(n_g, w_g, s_{wh}, \{T_\tau\}\right) \qquad (20)$$

Maximal value of a loading bay productivity $w_b^{\max}$ is achieved under the condition of absence of interoperable downtimes of handling mechanisms and could be defined as follows:

$$w_b^{\max} = n_g \cdot w_g \qquad (21)$$

A value of the loading bay productivity, close to its maximum, could be achieved through organizing the appropriate schedule $\{T_\tau\}$ of vehicles arrival to the loading bay. In this case the requests intervals are supposed to be not stochastic, which practically could be achieved only for relatively small polygons when servicing regular customers.

Actual productivity $w_b^{(f)}$ of a loading bay for the flow of $N_r$ requests is determined as the following ratio:

$$w_b^{(f)} = \frac{\sum\limits_{i=1}^{N_r} \omega_i}{\sum\limits_{i=1}^{N_r} \tau_{gi}} \qquad (22)$$

Intensity of the requests arrival and input parameters that determine the loading bay productivity are the factors, which directly affect the value of the waiting time duration $\tau_w^g$ caused by lack of unoccupied mechanism:

$$\tau_w^g = f\left(\xi, w_b\right) \qquad (23)$$

For the loading bays of a transport node that perform unloading operations for arrived vehicles, in the dependence (23) the intensity $\xi_{in}$ of incoming material flow is considered; for the loading bays performing loading operations the intensity $\xi_{out}$ of outgoing material flow is taken into account:

$$\begin{bmatrix} \tau_w^{(u)} = f\left(\xi_{in}, w_b^{TW}\right), \\ \tau_w^{(l)} = f\left(\xi_{out}, w_b^{WT}\right), \end{bmatrix} \qquad (24)$$

where:
$w_b^{TW}$ and $w_b^{WT}$ – productivity of loading bays of TW and WT respectively, t/h.

For the loading bays of direct transshipment the dependence of waiting time duration $\tau_w^g$ from the couple of values $\xi_{in}$ and $\xi_{out}$ is considered:

$$\begin{bmatrix} \tau_w^{(u)} = f\left(\xi_{in}, \xi_{out}, w_b^{TT}\right), \\ \tau_w^{(l)} = f\left(\xi_{in}, \xi_{out}, w_b^{TT}\right), \end{bmatrix} \qquad (25)$$

where:
$w_b^{TT}$ – productivity of the direct transshipment loading bay, t/h.

For the subprocess of servicing at the warehouse of a transport node, the influence of demand parameters on the subprocess is determined similarly – as the dependence of the subprocess time characteristics from numerical parameters of demand and input factors.

Duration $\tau_w^{wh}$ of waiting by the vehicle of the beginning of servicing, which is caused by lack of space in the warehouse, is determined with the intensity of outgoing material flow (intensity of removal from the warehouse), the available warehouse resources and the intensity of incoming material flow (intensity of shipments entry to the warehouse):

$$\tau_w^{wh} = f\left(\xi_{in}, \xi_{out}, s_{wh}\right) \qquad (26)$$

Duration of cargos storage in the transport node warehouse depends on the intensity of incoming and outgoing material flows and the numerical parameters that characterize the efficiency of servicing processes at the loading bays of TW and WT type:

$$\tau_{st} = f\left(\xi_{in}, \xi_{out}, w_b^{TW}, w_b^{WT}\right) \qquad (27)$$

Links of the $L_{EE}$ type, typical for the variant of servicing through the warehouse and for the mixed variant of servicing, are formalized as functional dependencies between the subprocesses characteristics: indicators, which characterize technological processes of the warehouse functioning, depend on characteristics of the loading bays efficiency (functional dependence (27)), and the efficiency characteristics of loading bays, in turn, are determined on the base of the warehouse parameters (dependence (20)).

Links of the $L_{EY}$ type formalize dependence of the efficiency criterion $K_e$ from the subprocesses characteristics for the model of a transport node functioning as a servicing system.

Expenses $E_\Sigma$ on the clients servicing for the specified variant of technological process are calculated as a sum of operating costs $E_{op}$ for servicing of the requests flows and expenses $E_d$ on the production resources downtime:

$$E_\Sigma = E_{op} + E_d \qquad (28)$$

Operating costs for servicing of the flow of $N_r$ requests (the cumulative flow – such that includes both the requests on unloading and the requests on loading operations) is determined as a sum of costs for servicing of separate requests:

$$E_{op}^w = \sum_{i=1}^{N_r} c_{wh(i)} + \sum_{i=1}^{N_r^l} c_{g(i)}^l + \sum_{i=1}^{N_r^u} c_{g(i)}^u \qquad (29)$$

$$E_{op}^d = \sum_{i=1}^{N_r} c_{g(i)}^d \qquad (30)$$

$$E_{op}^m = \sum_{i=1}^{N_r} c_{wh(i)} + \sum_{i=1}^{N_r^l} c_{g(i)}^l + \sum_{i=1}^{N_r^u} c_{g(i)}^u + \sum_{i=1}^{N_r^d} c_{g(i)}^d \qquad (31)$$

where:

$E_{op}^w$, $E_{op}^d$ and $E_{op}^m$ – operation costs for servicing variants of transshipments through the warehouse, direct transshipments and the mixed one respectively, \$,

$N_r^l$, $N_r^u$ and $N_r^d$ – number of requests that are serviced at the loading bays of loading, unloading and direct transshipments respectively.

Costs, related to the downtime of production resources of a transport node, are determined for the respective resources, used in the servicing process:

$$E_d = c_g' + c_{wh}' \qquad (32)$$

where:

$c_g'$ – costs related to the downtime of handling mechanisms while servicing the requests flow, \$,

$c_{wh}'$ – costs related to the storage area being idle while servicing the requests flow, \$.

Costs related to the handling mechanisms downtime are calculated on the base of the downtime duration for each mechanism at the loading bay:

$$c_g' = \upsilon_g' \cdot \sum_{j=1}^{n_g} \tau_{d(j)}^g \qquad (33)$$

where:

$\tau_{d(j)}^g$ – total downtime duration for the $i$-th mechanism while servicing the requests flow, h.

If it is known the value $s_{wh(0)}^f$ of the warehouse area, which is idle at the moment of the beginning of servicing of the flow of $N_r$ requests, then costs, related to downtime of free warehouse space while servicing process, could be determined in the following way:

$$c_{wh}' = \upsilon_{wh}' \cdot \sum_{i=1}^{N_r} \left[ \tau_{g(i)} \cdot \left( s_{wh(0)}^f + \omega_i \cdot \frac{\alpha_{wh}}{2} \right) \right] \qquad (34)$$

where:

$\tau_{g(i)}$ – duration of the $i$-th request servicing at the loading bay, h,

$\alpha_{wh}$ – coefficient of utilization of the warehouse area, m²/t.

The cost of production resources $C_R$ of a transport node functionally depend on input parameters – the storage area $s_{wh}$ and vector $\{n_g\}$. Respective functional dependencies could be presented in a form of linear functions on the base of average values of resources cost.

The cost of production resources $C_R^g$ for loading bays is determined as the product of a number of handling mechanisms and the average carrying value of one mechanism:

$$C_R^g = n_g \cdot B_g \qquad (35)$$

where:
$B_g$ – the average carrying value of one handling mechanism at the loading bay, \$.

The cost of production resources $C_R^{wh}$ for the transport node warehouse could be determined on the base of specific cost of a storage area:

$$C_R^{wh} = s_{wh} \cdot B_{wh} \qquad (36)$$

where:
$B_{wh}$ – specific cost of a storage area, \$/m².

## 5. Base classes for simulation model of the multimodal transport node functioning

In accordance with the used approach for formalization of research object the implementation of simulation model for the transport node functioning were carried out using the principles of object-oriented programming. As the main modeling tool the *TransportNode.dll* class library, developed by the authors, was used. The class library full code could be downloaded at (Naumov, 2015a). Software implementation of the base classes and simulation models for the processes of a multimodal transport node functioning were performed with the use of C# programming language.

The classes used as the base for simulations of the transport node technological processes are the following:
- *TransportHub*: allows describing of the multimodal transport node, where servicing of request flows with the defined characteristics is performed;
- *Warehouse*: is used for description of warehouses as elements of a multimodal transport node;

- *LoadingBay*: allows describing of the loading bay as the part of a multimodal transport node;
- *Gear*: is developed for simulations of functioning of the handling mechanism as an element of a loading bay of a transport node;
- *RequestFlow*: is used for modeling of a flow of requests on servicing in a transport node on the base of specified characteristics of flow parameters as stochastic variables;
- *Consignment*: allows the depiction of a single request on services of a transport node as an elementary unit of the requests flow;
- *TransportMode*: is developed for description of characteristics of the transport modes that interact in a transport node.
- Main fields of the *TransportHub* class are:
- collection *Flows* of the *RequestFlow* elements: contains objects that characterize flows of the requests on servicing in a transport node;
- collection *Bays* of the *LoadingBay* elements: reflects the loading bays as elements of a transport node – their numerical characteristics and functioning results;
- field *Warehouse* of the *Warehouse* type: reflects main characteristics of the warehouse functioning;
- property *Demand* of the *List<Consignment>* type: contains a set of requests from the *Flows* flows, which form the total demand for services of a transport node for all the modes of transport.

Modeling of objects of the *Warehouse* class is implemented on the base of following characteristics:
- field *TransportHub* of the *Hub* type: contains a reference on the transport node object, which part the warehouse object is;
- *Capacity* – numerical characteristic of the warehouse capacity, t;
- *Load* – numerical characteristic reflecting current cargo amount in the warehouse, t;
- *Square* – numerical characteristic reflecting the warehouse storage area, m²;
- collections *InFlow* and *OutFlow* of elements of the *Consignment* type: contain requests for outgoing and incoming flows, which were serviced during the modeling period.

Main characteristics of objects of the *LoadingBay* type are:
- field *TransportHub* of the *Hub* type: contains a reference on the transport node object, which part the loading bay object is;

- collection *Gears* of elements of the *Gear* type: contains references on objects that are the models of handling mechanisms, which operate as elements of a loading bay
- field *Demand* of the *RequestFlow* type: contains a reference on the requests flow that is a model of demand for services at the loading bay.

Objects of the *Gear* type are described on the base of the following fields of the class:

- field *Bay* of the *LoadingBay* type: contains a reference on the model of the loading bay;
- *Productivity* – numerical characteristic that reflects a productivity of the handling mechanism, t/h;
- numerical fields *CostsLoaded* and *CostsEmpty*: reflect specific costs of servicing process and of the mechanism downtime respectively, $/h;
- collection *ServicedRequests* of elements of the *Consignment* type: contains a list of requests, which were serviced by the handling mechanism during the modeling period.

The main characteristics of objects of the *RequestFlow* type are:

- field *duration*: returns numerical value of duration of the modeling period;
- objects *volume* and *interval* of the *Stochastic* type are program implementations of stochastic variables of the cargo volume and the requests interval; class *Stochastic* is contained in the *StochasticLib.dll* that was developed by authors (*StochasticLib.dll* is open source, its C# code could be downloaded at Naumov, (2015b));
- Boolean field *isLoaded*: has *true* value, if the flow characterizes requests on unloading operations in a transport node, has *false* value otherwise;
- collection *requests* of elements of the *Consignment* type: contains objects that characterize requests as the flow elements.

Objects of the *Consignment* type are characterized with the following fields:

- field *mode* of the *TransportMode* type: characterizes the transport mode for the request;
- field *volume* is numerical characteristic of cargo volume in the request, t;
- Boolean field *IsLoaded*: takes *true* value, if unloading operations are requested, takes *false* value otherwise;
- field *cow* is the request numerical characteristic that contains a value of specific cost associated with withdrawal of funds from circulation, $/(h×t);

- field *tAppear* contains the model time value of the request arrival, h;
- fields *TBeginService* and *TEndService*: contain the model time values of the beginning and end of the request servicing, h;

The *TransportMode* class allows describing of transport modes that interact in a transport node on the base of following characteristics:

- field *type* returns a code of the transport mode; in the *TransportMode* class the following internal constants are taken: ROAD = 1 (road transport), RAILWAY = 2 (railway transport), RIVER = 3 (river transport), SEA = 4 (sea transport), AIR = 5 (air transport);
- field *WaitTimeCosts* contains numerical value of specific cost on the vehicles downtime, $/h.

The main procedure that starts simulation process is the *Simulate* procedure of the *TransportHub* class.

## 6. Simulation results on the example of the "Amur-Harbor" loading area of Dnipropetrovsk River Port

As a base for practical verification of use of the proposed approach to transport node simulation, a transport node of Dnipropetrovsk River Port (DRP) was considered. In DRP the technological processes of interaction of the three modes of transport (river, rail and road transport) are carried out. DRP is a structural unit of the Ukrrichflot transport company and specializes in processing of a wide range of cargoes – grain, scrap metal, sand, gravel, feldspar, timber, equipment, and piece-goods in big-bags and on pallets. According to the official information (UKRRICHFLOT, 2015), the capacity of the port is 5,7 mln tons a year, and the total area of warehouses of port overcomes 69 ths square meters. The territory of the port includes two loading areas, 16 berths with a total length of berthing line 2500 m, where servicing of ships with a draft up to 4 m is possible. Production resources of DRP include 25 gantry cranes with capacity of 5 to 20 tons, 3 jib cranes with carrying capacity from 10 to 36 tons, an assembly crane with capacity of 75 tons, a heavy crane with capacity of 100 tons and 7 loaders with carrying capacity from 1,5 to 3 tons.

In DRP on the first berth of loading area "Amur-Harbor" operates grain elevators with a total capacity of 30 ths tons – 6 containers (silos) of 5 ths tons each. Grain elevator provides services on receiving of shipments at rail and road transport,

accumulation, storage, drying, cleaning, and shipment of grain, oil and industrial crops.

Studies of demand parameters, provided on the base of Dnipropetrovsk River Port, has shown that the shipment volume was normally distributed stochastic variable, and the requests interval had exponential distribution regardless of the transport mode for the requests in a flow. Obtained numerical characteristics of the demand parameters were used as input parameters in the simulation experiment.

In the simulation experiment three variants of material flow servicing were considered: transshipments through the warehouse, the direct transshipments and mixed variant of servicing. In order to ensure statistical significance of the experiment results, 100 runs for each servicing variant were conducted. Numerical results of the experiment are presented in Table 1.

Table 1. Numerical results of simulation experiment

| Characteristics | Servicing variant | | |
|---|---|---|---|
| | Transshipment through the warehouse | Direct transshipment | Mixed variant |
| Servicing prime cost, $/tons | 2,57 | 2,30 | 2,30 |
| Level of service | 0,8172 | 0,8175 | 0,8224 |
| Mean servicing duration, h/request | 3,76 | 8,64 | 6,22 |
| Mean duration of waiting for the beginning of service, h/request | 46,88 | 40,16 | 39,55 |
| Mean duration of downtime for handling mechanisms, h/request | 10,28 | 11,14 | 13,91 |
| Logistics management efficiency criterion | 0,4172 | 0,5753 | 0,3721 |

The mixed variant of servicing in the conducted experiment was implemented for the following strategy: a half of the received requests in a random order are serviced through the warehouse, and other requests – with the use of direct variant. It should be mentioned that content and effectiveness of

servicing strategies for the mixed variant is a subject to additional research.

While analyzing results of the experiment, the level of service was evaluated as a ratio of a number of serviced requests to the total number of received requests on services of a transport node.

Initial analysis of the results of the simulation experiment allows suggestion that for the loading area "Amur-Harbor" of DRP the most appropriate from the standpoint of the logistics management efficiency is mixed variant because it is characterized by the lowest value of the efficiency criterion. The mixed variant is also characterized by a somewhat higher value of level of the material flow service (level of service is higher by 0,5% compared to the direct transshipments and the transshipment through the warehouse). On the efficiency criterion of the logistics management, for the loading area "Amur-Harbor" of DRP the least efficient variant of material flow servicing is direct transshipments. According to the prime cost of servicing, the least efficient is servicing through the warehouse. It also should be mentioned that servicing through the warehouse is characterized with the minimal values of handling mechanisms downtime, but for this variant duration of waiting for the beginning of service is the biggest.

## 7. Conclusions

On the base of presented dependencies it is possible to solve the problems of logistics management in multimodal transport nodes. Dependencies of the proposed efficiency criterion from numerical characteristics of input parameters could be considered as known, if functional dependencies (20) and (24)–(27) are formalized. It should be mentioned that determination of such a type of dependencies is possible on the basis of statistical analysis of simulations results, which could be obtained using the proposed software implementation of a transport node model.

Presented approach to simulation of a transport node allows studying the influence of numerical parameters of production resources and organizational impacts on efficiency of the node functioning. Development of software models using the proposed base classes allows obtaining an effective tool for solving practical problems of logistic management in multimodal transport nodes.

## References

[1] BOZARTH, C.C. and HANDFIELD, R.B., 2006. *Introduction to operations and supply chain management.* Upper Saddle River, New Jersey: Prentice Education Inc.

[2] FENG-LING, L. and ZHENG-YI, G., 2006. Synthetic Evaluation on Transfer of Rail Transit Terminal Based on AHP Method [J]. *Railway Transport and Economy,* 2006-04, pp. 79-81.

[3] FLÓREZ, J.E., DE REYNA, A.T.A., GARCÍA, J., LÓPEZ, C.L., OLAYA, A.G. and BORRAJO, D., 2011. Planning Multi-Modal Transportation Problems. *Proceedings of the Twenty-First International Conference on Automated Planning and Scheduling* 2011, Association for the Advancement of Artificial Intelligence, pp. 66-73.

[4] LI, G., HU, D. and SU, L., 2013. The Model of Location for Single Allocation Multimodal Hub Under Capacity Constraints. *Procedia-Social and Behavioral Sciences,* 96, pp. 351-359.

[5] MAHROUS, R.F., 2012. *Multimodal transportation systems: Modelling challenges. Thesis.*, University of Twente.

[6] NAGORNYI, I.V., NAUMOV, V.S. and LITVINOVA, Y.V., 2014. Systemnyi pidhid do optymizatsiji protsesiv logistychnogo upravlinnia v transportnyh vuzlah. *Zheleznodorozhnyj transport Ukrainy,* 3(106), pp. 46-51.

[7] NAUMOV, V.S., 2012. *Transportno-ekspieditsionnoje obsluzhivanije v logisticheskih sistemah.* Kharkiv: KhNAHU.

[8] NAUMOV, V.S., 2013. *Razvitije nauchno-tehnologicheskih osnov ekspeditorskogo obsluzhivanija na avtomobilnom transporte.* Kharkiv National Automobile and Highway University.

[9] NAUMOV, V.S., 2015a-last update, C# Code for Simulation of Transport Hub Functioning. Available:https://www.academia.edu/1647262 6/C_Code_for_Simulation_of_Transport_Hub_Functioning.

[10] NAUMOV, V.S., 2015b-last update, C# Code for Generation of Stochastic Values. Available: https://www.academia.edu/11183292/C_code_for_generation_of_stochastic_values.

[11] RACUNICA, I. and WYNTER, L., 2005. Optimal location of intermodal freight hubs. *Transportation Research Part B: Methodological,* 39(5), pp. 453-477.

[12] STOCK, J.R. and LAMBERT, D.M., 2000. *Strategic logistics management.* New York: McGraw-Hill/Irwin Boston, MA.

[13] SUN, Q. and CHENG, D., 2010. An Empirical Study of Fuzzy Quality Synthetic Evaluation of Comprehensive Transfer Hub Transfer Articulation. *Technological Innovation Management,* 31, pp. 164-166.

[14] UKRRICHFLOT, 2015-last update, Natural logistics. Available: http://ukrrichflot.ua/en/.

[15] ZAMENI, S. and RAZMI, J., 2015. Multimodal Transportation p-hub Location Routing Problem with Simultaneous Pick-ups and Deliveries. *Journal of Optimization in Industrial Engineering,* 8(17), pp. 11-20.