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Determination of the Optimal Number of Forklifts in the Distribution Center Using the Queuing Network Model

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ABSTRACT

The functioning of modern distribution centers is impossible without the effective organization of the work of mobile material handling equipment, which is the main means of processing cargo flows in warehouses and directly affects the costs and time of warehouse operations. The article proposes the mathematical model for determining the optimal number of forklifts in the distribution center based on integer programming using the open queuing network model. The model reflects the peculiarities of the technological process of cargo handling in the distribution center and the participation of forklifts in it. Given the impossibility of using exact optimization methods because of the type of the objective function, the heuristic method is proposed for solving the problem, which allows for avoiding the complete enumeration of solutions and finding the optimal number of forklifts in a short time, considering different scenarios and operating modes of the distribution center. The advantage of this heuristic algorithm is its ability to determine the optimal number of service channels in high dimensional open queuing networks. The minimum of total service costs, which include operating costs for the maintenance of forklifts and cargo flow handling costs, were used as an optimization criterion. The model is an effective tool for decision making when equipping distribution centers with mobile material handling equipment.

Keywords: *cost, distribution center, heuristic method, model, optimization, queuing network*

1. INTRODUCTION

Warehouses help to eliminate irrational transportation, increase the rhythm and organization of production, marketing and transport operations, reduce inventory for manufacturers, wholesalers, and retail trade networks.

Distribution centers are warehouses that provide acceptance of goods from suppliers - manufacturers or large wholesalers, their placement, temporary storage, packaging, and shipment to retail chains, forming one of the main logistics subsystems of supply chains. They play an important role in the distribution of goods to retailers or small wholesalers and have a significant impact on the overall distribution of goods. Distribution centers differ from ordinary warehouses in that they do not store goods for a long time but ensure their accumulation in the face of possible fluctuations in supply and demand. They are a kind of buffer that creates the safety stock of goods, helping to smooth out fluctuations in demand for goods by increasing the volume of shipments, even if there were supply disruptions (Ali & Nakade, 2015). To implement these modes of service, distribution centers use both temporary storage of goods and cross-docking – the process of accepting and shipping goods through the warehouse directly, without placing it first into storage locations.

Effective management of distribution centers increases the competitiveness of supply chains by lowering operating costs, improving warehouse equipment productivity and customer satisfaction. Warehouse operations are one of the most important components in the pricing and delivery time of goods, providing technical, technological, and planning-organizational interconnection of intra-warehouse processes with processes taking place in supply chains. Warehouse costs and the time of warehouse processing of goods are determined by the amount and characteristics of technological equipment used for unloading them from vehicles delivering goods from suppliers, placing in the warehouse, selecting for picking customer orders, transporting between warehouse sections, and loading onto vehicles for shipment to customers (Lerher *et al.*, 2012; Karasek, 2013). Lack of efficient technical systems in logistics is among the ten most crucial challenges identified by Gupta *et al.* (2018) based on a review of literature and expert opinions that affect the quality assurance and cost of logistics services. Therefore, the organization of the work of warehouse technological equipment is a potential direction for improving the work of distribution centers, characterized by large areas and high level of cargo turnover. The use of forklifts, automated guided vehicles, pallet trucks, lifts and stackers in the work of distribution centers significantly reduces the cost and time for performing warehouse operations for handling cargo flows.

Determination of the required number of mobile material handling equipment is one of the key tasks of warehouse management and depends on the arrival intensity of the goods at the warehouse, the volume of processed goods, their packaging and weight, organization schemes for technological process of handling goods in the warehouse, the parameters of the warehouse, and the characteristics of the equipment itself (Longo, 2011; Kay, 2012; Šaderová and Ambriško, 2017). The essence of this task lies in the correct determination of the number of used mobile material handling equipment in the distribution center (DC) in terms of its effective use in organizing the processing of cargo flows and the associated costs.

The solution to this problem is based on a well-known contradiction: on the one hand, the excessive number of mobile material handling equipment leads to its downtime and a decrease in the efficiency of the distribution center (Zabara *et al*., 2015), on the other hand, the lack of mechanisms leads to the accumulation and increase of time handling of goods in certain areas of the warehouse (Yaxiong *et al*., 2010). From the point of view of a systematic approach and logistics management principles, the task of organizing loading and unloading operations in the DC is to determine the number of mobile material handling equipment, in which the optimization of the overall effect should be ensured in the form of minimal economic losses for all participants in logistics processes: carriers of goods distribution center owners, etc. This necessitates a search for reasonable compromise between the indicators of cargo flows processed at the warehouse and the characteristics of warehouse technological equipment.

Let us consider the solution to this issue using the example of forklifts, which are the most common, versatile, productive and expensive motorised material handling equipment in distribution centers. According to analysts, the global forklifts market was valued at $ 45.01 billion in 2019 and is projected to reach $ 81.40 billion by 2027 (Jadhav and Mutreja, 2021).

Thus, the study is aimed at optimizing the operation parameters of the DC based on the development of an economic and mathematical model for determining the optimal number of forklifts, which ensures the minimum total cost of servicing cargo flows, including the cost of maintaining forklifts and the cost of processing cargo flows in the DC, considering the peculiarities of its organization and functioning.

2. LITERATURE REVIEW

Review literature discusses various problems related to the operation and modelling work of forklifts in warehouses (Gu *et al*, 2007; Yener and Yazgan, 2019). The regression model, obtained based on the full factorial experiment, revealed that the number of loading and unloading mechanisms had the greatest impact on the unit costs associated with cargo handling in the transport and storage complex, which necessitates their rationalization (Shramenko, 2015). Research by Abideen & Mohamad (2021) showed that the apple of an integrated approach of the value stream mapping and the discrete event simulation technique made it possible to improve the warehouse performance metrics, including an increase forklift throughput usage percentage. A wide range of multi-criteria methods and their combinations are used to evaluate and select the best types of forklifts for warehouse (Pamučar and Ćirović, 2015; Průša *et al.*, 2018; Fazlollahtabar *et al.*, 2019). Chan (2002) described the intelligent material handling equipment selection system called MHESA (Material Handling Equipment Selection Advisor) that is composed of three modules: a database to store equipment types with their specifications; a knowledge-based expert system for assisting mobile material handling equipment selection; and an analytic hierarchy process model to choose the most favourable equipment type. Oliveira (2007) proposed the procedure for sorting pallets, based on genetic algorithms, for the simultaneous loading of the truck using forklifts, which minimizes their working time. Zhang *et al.* (2009) developed a set of probabilistic and physics-based models that minimize the total expected service time of the workflow, taking into account interruptions in the handling of loading and unloading equipment resulting from high loads, by changing the route of their movement in the congested warehouse area. Estanjini *et al.* (2011) described the forklift operation control system in the commercial warehouse using the mobile wireless sensor network that can improve their dispatching and reduce the costs associated with truck loading/unloading delays by collecting information about the location and quantity of goods in the warehouse. Öztürkoğlu & Hoşer (2019), in a study of the impact of operational and design parameters on picking cycle times in a traditional two-block warehouse layout, showed that increased aisle congestion affects the operation of forklifts and autonomous vehicles, which requires the organization of optimal routes. Beker *et al.* (2012) researched the shortest path algorithms for forklifts routing optimization, which leads to reduction of work in the warehouse. Dharmasiri *et al.* (2020) evaluated several algorithms for path planning and traffic control of mobile equipment in a warehouse and developed a multiple automated ground vehicles traffic real time control algorithm for warehouse operations using the Djikstra approach, which provides collision avoidance between them.

The main tool for researching warehouse operations using loading and unloading mechanisms is simulation. Simulation modelling of non-automated distribution warehouses showed the importance of forklifts in achieving effective service of material flows in the warehouse (Takakuwa *et al*., 2000; Medina *et al*., 2009). Burinskiene (2015) suggested the simulation model of work of forklift, which optimizes the routes of its movement, taking into account the width of the aisles in the warehouse under different working scenarios. Pawlewski (2015) developed the simulation model, which used the method that combines DES (Discrete Event) and ABS (Agent Based Simulation), which made it possible to organize the motion of forklifts in the warehouse based on picking lists. Shepelev *et al.* (2018) developed methodology for calculating the optimal number of loading and unloading mechanisms and stations, which provide minimum aggregate costs for loading and unloading operations incurred by transport and warehouse complexes and the downtime of rolling stock in the course of loading and unloading operations. Galehhondabi and Massel (2018) proposed the storage space allocation model that considers the availability of the fleet of forklifts in the warehouse. The model uses the criterion of minimizing idle time and overtime of forklifts during the whole scheduled warehousing period. Šaderová *et al.* (2018) proposed the methodology for determining the required number of forklifts, which uses the simulation model and consists of three stages: analysis of forklift activities, determination of the required number of forklifts and verification of activities of the calculated number of forklifts. Rozhnov (2019) implemented in the Any Logic system the simulation model of the processes of unloading pallets from trucks and placing them in the cells of the front racks of the warehouse using agent-based and discrete-event approaches, which allows optimizing the number of forklifts according to the criterion of their average load. Carli *et al.* (2020) developed the two-step optimization model based on integer programming to automatically identify an optimal schedule of the material handling activities forklifts in labor-intensive warehouses using the criterion minimizing the total cost, which is the sum of the penalty cost related to the make span of the material handling activities and the total electricity cost of charging batteries. Ghomi *et al.* (2022) developed a mixed integer non-linear programming model that allowed to optimize forklift utilization by minimizing the total transshipment costs and control the forklift congestion needed to transfer products in cross-docking terminals by minimizing the total number of forklifts.

A characteristic feature of distribution centers is the presence of probabilistic parameters of functioning due to uneven receipt of goods, different size of consignments, unbalanced handling of goods in different parts of the warehouse, uneven demand for processing freight traffic over time, inconsistency in the volume of work in the warehouse, blockages during operation of forklifts and other reasons. (Ardakani and Fei, 2020). The stochastic nature of the functioning of warehouses is best described using queuing models (Gong and de Koster, 2011; Rashid *et al.*, 2015). However, the application of its mathematical apparatus for modelling the operation of warehouses is limited to the simple queuing system (QS) of the M/M/C type, where forklifts are servers. Anand *et al.* (2014) uses this system in the model for evaluating the efficiency of energy management for forklifts. Stojčić *et al.* (2018) also used this system to develop the ANFIS (Adaptive neuro-fuzzy inference system) model in the warehouse system with two servers to optimize vehicle service by the criterion of time. Veljović (2017) applied the queuing model M/M/C to determine the number of technological equipment in the warehouse, including forklifts that unload/load trucks, by taking into account all costs that depend on their number. Goodarzi *et al.* (2020) investigated the vehicles routing problem for the multi-door cross-docking system at the distribution warehouse using the multi-channel queuing system. To solve the problem of optimizing the waiting cost and waiting time of vehicles in the queue, the genetic algorithm was used. Lamballais *et al.* (2017) proposed a queuing network model for a robotic warehouse for order picking in e-commerce fulfillment centers that analytically estimate maximum order throughput, average order cycle time and robot utilization. Examples of using queuing theory to optimize warehouse processes taking into account the operation of forklifts are also given in articles by Masek *et al. (2015), Alnahal and Ahrens (2018).*

Existing studies of this problem do not take into account the multi-stage, branching and multivariance of the technological process in the DC and do not study the structure of the total costs of servicing cargo flows by forklifts in the DC. Therefore, the development of an economic and mathematical model for determining the optimal number of forklifts, which would take into account the characteristics of the organization, the streaming nature of the processes of receipt and processing of cargo flows, and other critically important parameters of the distribution center functioning process, is relevant.

3. METHODOLOGY

For the most efficient operation of DC, a "zone" structure of the warehouse is used, i.e., its territory is divided into technological areas. This allows to control the internal movement of goods in the best possible way, provide quick and easy access to them, save warehouse resources (equipment, personnel, time), and also make it possible to maximize the use of DC space, which contributes to increasing its profitability.

The technological process of processing goods in DC consists of several main operations in the corresponding areas: unloading and receiving goods, placing them in storage, selection and completing orders, shipping goods to be sent to customers.

Considering the possible ways of processing goods in DC (with temporary storage and cross-docking), the following types of material flows in the warehouse are distinguished:

- Incoming – in the areas of unloading and receiving goods.
- Internal for storage – from the receiving area to the storage area.
- Internal through for picking – from the acceptance area to the picking and forwarding area.
- Internal through for shipment – from the receiving area to the goods shipment area.
- Internal for shipment – from the storage area to the picking and forwarding area.
- Outcoming – from the picking and forwarding area to the shipment area of the picked goods orders.

The main technological areas, with the scheme of work and the main material flows in DC are shown in **Figure 1**.

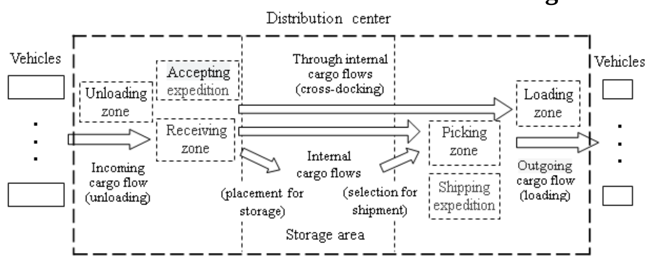


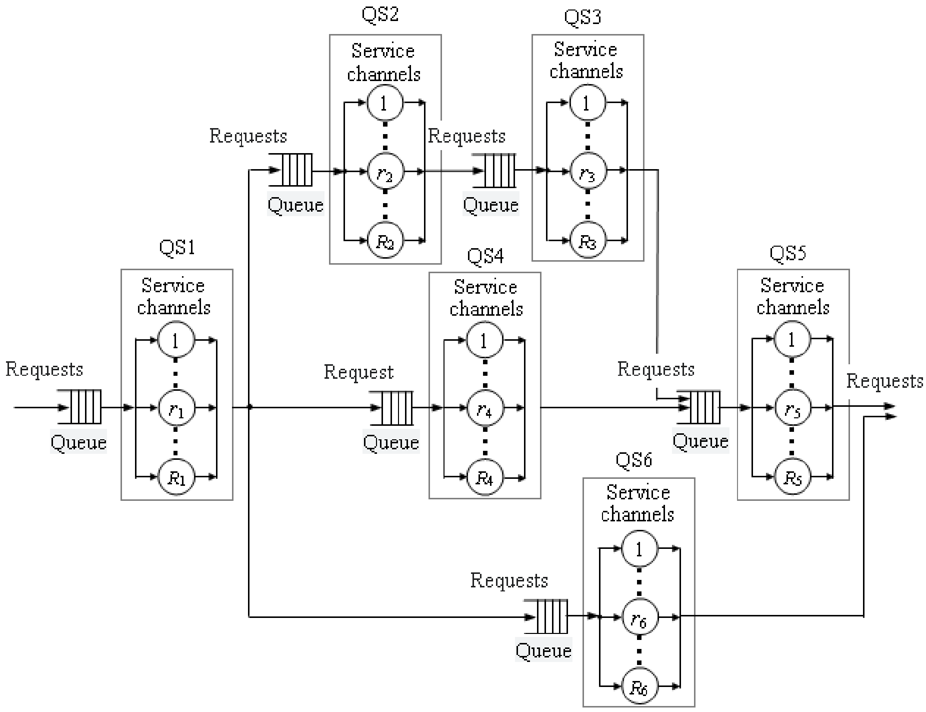
Figure 1 Structure and scheme of material flows of the distribution center

Suppose that pallets are the only loading unit used to move and store products in all areas of the warehouse, so all handling in the warehouse is performed by forklifts. Distribution centers operate continuously, i.e., warehouse operations can be carried out simultaneously in different technological areas using different forklifts. Thus, forklifts are the resource that is distributed between various warehouse operations and material (cargo) flows.

Taking into account the organization of the movement of material flows between the technological areas of DC, we present the diagram of the process of servicing the flows of cargo units in the warehouse using forklifts in the form of the open queueing network (OQN). The cargo units that are processed in the warehouse are described in the form of service requests, the possible directions of movement of goods between the technological areas of DC in the form of queuing systems, and forklifts - in the form of service channels in each QS. In the open queuing network, requests come from the endless external source - the unloading of goods delivered to the warehouse by vehicles from suppliers and leave the network after the completion of the service - the shipment of goods from the warehouse to vehicles for sending them to customers. Queuing systems are described using the following components: incoming request flow, queue discipline and service mechanism. Each QS consists of several identical service channels with the common queue, i.e., the multi-channel system.

The OQN in question consists of six interconnected queuing systems that service the flow of requests passing through the network:

- QS1 – unloading of goods.
- QS2 – placement for temporary storage.
- QS3 – selection for order picking.
- QS4 – dispatch for re-picking of cargo.
- QS5 – shipment of goods to be sent to customers.
- QS6 – goods pass through the DC for shipment as an unchanged separate order (**Figure 2**).



R1, R2, R3, R4, R5, R6 – the number of service channels in the corresponding queuing systems.
Figure 2 An open queuing network model which describes the operation of forklifts in a distribution center

The incoming flow is characterized by the probabilistic law of the distribution of the moments of arrival of requests in the OQN and the number of requests in each arrival. We will assume that all incoming flows in the OQN are Poisson, due to the limiting properties of the Poisson flow, this assumption is usually not excessive. This means almost a zero probability of simultaneous receipt of more than one request (ordinariness of the flow); all requests that make up the flow arrive at random time points independently of each other (absence of aftereffect); the probability of k requests appearing at any time interval depends only on the number k and on the duration t of the interval and does not depend on the beginning of its countdown (flow stationarity).

The main characteristic of the flow of requests is the average value of the duration of the intervals between the moments of their arrivals τ, which for the random variable is the mathematical expectation $M[\tau]$. The parameter inverse to the mathematical expectation is the average rate of requests arriving per unit of time λ.

All requests coming to the certain QS form the single queue to it. In each QS, any of the service channels accepts the next request for servicing either at the time of its arrival, if the channel is free at that moment, or from the queue at the time of completion of servicing of the earlier received request. The selection of service requests in each individual QS is carried out in accordance with the accepted discipline of the queue - service in the order of arrival FIFO (first in first out) - "first come, first served". Considering that all goods arriving at the DC must be accepted, processed and subsequently sent to the appropriate customers, the queues of all QSs are infinite, so that the probability of refusal to service requests is zero.

The service mechanism in each channel is characterized by the service time of one request, which covers the entire technological cycle of mechanized loading and unloading operations, including the movement of the forklift without cargo. The channel has the independent and identical exponential distribution of service time with the average t^S. The inverse of the average service time is the average service rate μ. Since the volumes of work of forklifts in the certain technological area of the DC are approximately the same, the average service rates in each channel of i^{th} QS will be denoted by the parameters μ_i, $i = \overline{1,6}$.

Under these formulated conditions, the operation of each technological area of the DC is described by the QS *M/M/c* model, and the investigated OQN is exponential.

All requests arriving at the OQN, depending on the method of cargo handling in the distribution center, are served by the certain number of QSs, therefore, the routes of their movement in the network can be specified using the stochastic indecomposable matrix: $\Theta = \left\|\theta_{ij}\right\|; \, i, j = \overline{0,6}$, where θ_{ij} – the probability that after service in i^{th} QS, the request will go to j^{th} QS. Probabilities θ_{01} and θ_{50}, θ_{60} – are, respectively, the probability of the request in QS1 from the external source (unloading of goods) and the probability of leaving the network by requests after the end of service in QS5, QS6 systems (shipment of goods).

In this case, the equality is fulfilled:

$$\sum_{j=0}^{6} \theta_{ij} = 1; \; i = \overline{0,6}, \text{ where } \theta_{ii} = 0. \tag{1}$$

In the stationary mode, the intensities of the input and output flows for any QS of the OQN will be equal to each other. Such a mode in the OQN is possible if for each i^{th} QS the intensity of the incoming flow of requests is less than the intensity of their service:

$$\lambda_i < \mu_i R_i; \; i = \overline{1,6}, \tag{2}$$

where R_i – the number of service channels in i^{th} QS.

The intensities of the flows of requests entering in j^{th} QS satisfy the following system of linear relations:

$$\lambda_j = \sum_{i=0}^{6} \lambda_i \theta_{ij}; \; j = \overline{1,6}, \text{ where } i \neq j. \tag{3}$$

The state of the given OQN at the arbitrary moment of time is determined by the vector $n = (n_1,...,n_i,...,n_6)$, where n_i - the number of requests in the queue and on service in i^{th} QS, $i = \overline{1,6}$. According to Jackson's theorem (Walrand, 1988), the stationary probability distribution of network states exists and has the form:

$$P(n_1,...,n_i,...,n_6) = \prod_{i=1}^{6} P_i(n_i), \tag{4}$$

where $P_i(n_i)$ is the stationary probability of finding n_i queries in i^{th} QS with parameters: $\lambda = \lambda_i$, $\mu = \mu_i$ and $c = R_i$.

Thus, the study of the OQN is reduced to the study of the totality of its constituent independent QSs. In this case, the function $P(n)$ for any QS of the given QN for the case $\frac{\lambda}{\mu R} < 1$ calculated as:

$$P(n) = \left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!} P_0, \; 1 \le n \le R; \tag{5}$$

$$P(n) = \left(\frac{\lambda}{\mu}\right)^n \frac{1}{R!\,R^{n-R}} P_0, \; n > R, \tag{6}$$

where P_0 is the probability that there is not a single request in the system (all serving channels are free):

$$P_0 = \left[\sum_{n=0}^{R} \left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!} + \left(\frac{\lambda}{\mu}\right)^{R+1} \frac{1}{R!\left(R - \frac{\lambda}{\mu}\right)}\right]^{-1}. \tag{7}$$

In case of $\frac{\lambda}{\mu R} \ge 1$ the queue of requests for service in the QS grows indefinitely, which is of no practical interest for study.

Determining the optimal number of forklifts in the warehouse requires finding solutions using the criterion of economic efficiency. It is proposed to use the criterion of the minimum total costs, including both the cost of maintaining forklifts (equipment costs, including maintenance, materials, labour, etc.), and the cost of handling cargo flows in the distribution center. These two types of costs are in conflict, because the increase in one automatically causes the decrease in the other, or vice versa.

Operating costs for the maintenance of forklifts are determined by the number of service channels in i^{th} QS R_i, $i = \overline{1,6}$, the cost of maintaining one service channel (forklift) in the system per unit of time (euros an hour, €/h) C_1^{fm} and the intensity of input flows of requests (cargo) in i^{th} QS λ_i, $i = \overline{1,6}$:

$$C^{fm} = C_1^{fm} \sum_{i=1}^{6} \frac{R_i}{\lambda_i}. \tag{8}$$

The costs of handling cargo flows in the DC are determined by the value of the specific losses C_q, associated with the stay in the queue of one cargo unit during the unit of time and the average waiting time for requests in the queue for each QS T_i^q:

$$C^{ch} = C^q \sum_{i=1}^{6} T_i^q, \tag{9}$$

where average waiting time for requests in the queue for i^{th} QS is defined as:

$$T_i^q = \frac{\left(\frac{\lambda_i}{\mu_i}\right)^{R_i+1}}{R_i R_i! \left(1 - \frac{\lambda_i}{\mu_i R_i}\right)^2} P_0. \tag{10}$$

Thus, the total costs of servicing cargo flow by forklifts in the DC per unit of time are equal to:

$$C = C_1^{fm} \sum_{i=1}^{6} \frac{R_i}{\lambda_i} + C^q \sum_{i=1}^{6} \frac{\left(\frac{\lambda_i}{\mu_i}\right)^{R_i+1}}{R_i R_i! \left(1 - \frac{\lambda_i}{\mu_i R_i}\right)^2} P_0. \tag{11}$$

The mathematical model for optimizing the total costs of servicing cargo flows by forklifts per unit of time has the form:

$$C = C_1^{fm} \sum_{i=1}^{6} \frac{R_i}{\lambda_i} + C^q \sum_{i=1}^{6} \frac{\left(\frac{\lambda_i}{\mu_i}\right)^{R_i+1}}{R_i R_i! \left(1 - \frac{\lambda_i}{\mu_i R_i}\right)^2} P_0 \to \min; \tag{12}$$

$$R_i \ge \left[\frac{\lambda_i}{\mu_i}\right] + 1, \; i = \overline{1,6};$$

$$R_i = [R_i], \; i = \overline{1,6};$$

$$\sum_{i=1}^{6} R_i \le N,$$

where $[\frac{\lambda_i}{\mu_i}]$ – integer part of $\frac{\lambda_i}{\mu_i}$;

$[R_i]$ – integer part of R_i;

N – the maximum possible number of forklifts in the distribution center, which is determined by the limited financial resources allocated for their maintenance within the given period of time.

This task is the integer programming task. With the small number of variables R_i determination of the optimal number of forklifts in the DC can be carried out by exhaustive search. The use of known exact methods for solving the problem under consideration, according to the authors, is not possible due to the form of the objective function (11). In this paper, we propose the heuristic method that allows to find the approximate solution to problems of the form (12) for the sufficiently large dimension. The content of the heuristic is as follows: at each iteration of the proposed algorithm, the number of service channels increases by one for the QS with the highest load intensity until the objective function decreases (11), or until the number of forklifts exceeds their specified maximum number. Note that in this case, the values of the intensities of the loads of the QS are equalized: $\rho_i = \frac{\lambda_i}{\mu_i R_i}, i = \overline{1,6}$.

The algorithm for implementing the proposed heuristic method for solving the problem of determining the optimal number of forklifts in the DC is shown in **Figure 3**.

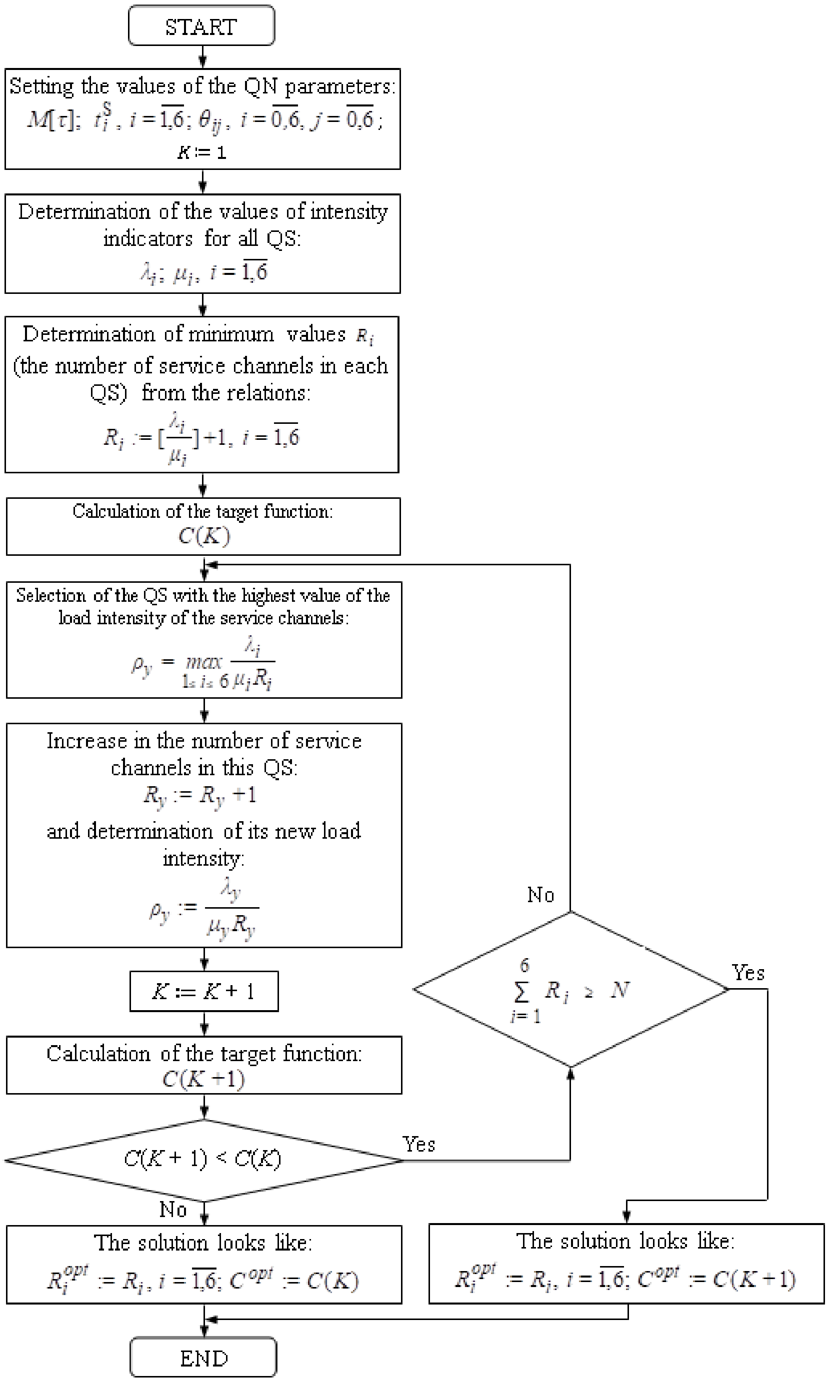


Figure 3 Scheme of the heuristic algorithm for determining the optimal number of forklifts in the distribution center

4. RESULTS

The effectiveness of the proposed heuristic algorithm was tested on the example of determining the optimal number of forklifts for the distribution center of the regional retail trade network "ROST" in the city of Kharkiv (Ukraine), which serves 7 supermarkets.

Several options for the values of the parameters of the work process of the DC were considered, which reflect the basic conditions and modes of its operation:

- The mathematical expectation of the duration of the intervals between the moments of arrival of cargo units to the distribution center.
- Average service time of one cargo unit in the technological areas of the distribution center.
- The probabilities of the transfer of cargo units between the technological areas of the distribution center.

It should be emphasized that the values of the considered parameters of the distribution center functioning process do not affect the structure of the model of the open queuing network.

The routes of movement of goods during their processing in the DC, which are shown in the model in **Figure 2**, are specified using the stochastic indecomposable matrix of transition probabilities:

$$\Theta = \begin{Vmatrix} 0 & \theta_{01} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \theta_{12} & 0 & \theta_{14} & 0 & \theta_{16} \\ 0 & 0 & 0 & \theta_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \theta_{35} & 0 \\ 0 & 0 & 0 & 0 & 0 & \theta_{45} & 0 \\ \theta_{50} & 0 & 0 & 0 & 0 & 0 & 0 \\ \theta_{60} & 0 & 0 & 0 & 0 & 0 & 0 \end{Vmatrix} \quad (13)$$

Variants of the values of the parameters of the process of functioning of the distribution center, which reflect different modes of its operation, and their brief description are shown in **Table 1**.

The operating costs of maintaining forklifts in the DC include:

- Depreciation deductions.
- Repair and maintenance costs.
- Fuel costs.
- Tire costs.
- Remuneration of the employee working on the forklift.

In most cases, electric forklifts are used in closed distribution centers, which are more environmentally friendly and safer for both humans and the environment, while quiet operation and vibration-free operation guarantee the comfortable environment for the operator. The average annual cost of operating one electric warehouse forklift with the lifting capacity of 1.5-2.0 t in two-shift operation (3130 h) is about € 9900, i.e., 3.16 € / h.

In the context of the difficulty of determining the specific losses associated with the stay of cargo units in the queue for service, to simplify the calculation of the total costs of service in the distribution center, it is proposed to use the ratio of operating costs for maintaining the forklift and specific losses associated with the stay of cargo units in the queue for service, $C^1_{\text{fm}} / C_{\text{q}}$, which will also allow us to study their influence on the results of solving the problem.

Table 1 Values and descriptions of the main parameters of the distribution center functioning process

Parameters	The Values		
	Variant 1	Variant 2	Variant 3
1. Mathematical expectation of the duration of intervals between the moments of arrival of cargo units to the distribution center, min.	$M[\tau]_{min} = 4$ high intensity of goods arrival – 150 pallets during working day (λ1)	$M[\tau]_{AV} = 6$ average intensity of goods arrival – 100 pallets during working day (λ2)	$M[\tau]_{max} = 8$ low intensity of goods arrival – 75 pallets during working day (λ3)
2. Average time of service by forklifts of one loading unit in the technological areas of the distribution center, min.	$t_1^S = 4; t_2^S = 5; t_3^S = 5;$ $t_4^S = 6; t_5^S = 7; t_6^S = 8$ high intensity of cargo handling (M1)	$t_1^S = 6; t_2^S = 7; t_3^S = 7;$ $t_4^S = 8; t_5^S = 9; t_6^S = 10$ average intensity of cargo handling (M2)	$t_1^S = 8; t_2^S = 9; t_3^S = 9;$ $t_4^S = 10; t_5^S = 11; t_6^S = 12$ low intensity of cargo handling (M3)
3. Probabilities of the transfer of cargo units between the technological areas of the distribution center	$\theta_{01} = 1; \theta_{12} = 0{,}7; \theta_{14} = 0{,}15;$ $\theta_{16} = 0{,}15; \theta_{23} = 1; \theta_{35} = 1;$ $\theta_{45} = 1; \theta_{50} = 1; \theta_{60} = 1$ rvice with temporary storage of good dominant (v1)	$\theta_{01} = 1; \theta_{12} = 0{,}4; \theta_{14} = 0{,}4;$ $\theta_{16} = 0{,}2; \theta_{23} = 1; \theta_{35} = 1;$ $\theta_{45} = 1; \theta_{50} = 1; \theta_{60} = 1$ service with multi-stage cross-docking dominant (v2)	$\theta_{01} = 1; \theta_{12} = 0{,}4; \theta_{14} = 0{,}2;$ $\theta_{16} = 0{,}4; \theta_{23} = 1; \theta_{35} = 1;$ $\theta_{45} = 1; \theta_{50} = 1; \theta_{60} = 1$ service with one-step cross-docking dominant (v3)

Assumptions and limitations adopted in the calculations:

- Loading units of the same type – pallets 800×1200×144 mm. (ISO1).
- Forklifts of the same type, which can only carry one pallet at a time.
- Each forklift is assigned to the specific technological area of the distribution center.
- The maximum possible number of electric forklifts for the investigated distribution center is limited to $N = 12$ units.
- The unit of measurement of the rates of arrival and servicing of cargo flows is the number of pallets per hour, (PLT/h).

Let us consider in detail the work of the heuristic algorithm in determining the optimal number of forklifts using the example of three options for the values of the parameters of the functioning of the DC under study with the ratio of operating costs for maintaining the forklift and specific losses associated with the stay of load units in the queue for service, $C_{\text{fm}}^{1} / C_{\text{q}} = 3/1$.

Example 1: For all parameters – variant 1 (**Table 2**).

Table 2 Values of indicators for finding the optimal solution using the heuristic algorithm (Example 1)

	i	**1**	**2**	**3**	**4**	**5**	**6**	***i***	**1**	**2**	**3**	**4**	**5**	**6**	$\sum_{i=1}^{6} R_i$	C^{opt}, **€/h**
	$M[\tau]$, min.	4														
	λ_i	15,0	10,5	10,5	2,25	12,75	2,25									
	t_i, min.	4	5	5	6	7	8									
	μ_i	15,0	12,0	12,0	10,0	8,571	7,5									
	$\frac{\lambda_i}{\mu_i}$	1,0	0,875	0,875	0,225	1,4876	0,3									
K=1	ρ_i	0,5	0,875	0,875	0,225	0,7438	0,3	R_i	2	1	1	1	2	1	8	5,82
K=2	ρ_i	0,5	0,4375	0,875	0,225	0,7437	0,3	R_i	2	2	1	1	2	1	9	5,53
K=3	ρ_i	0,5	0,4375	0,4375	0,225	0,7437	0,3	R_i^{opt}	**2**	**2**	**2**	**1**	**2**	**1**	**10**	**5,24**

Example 2: Parameter 1 – variant 2; parameter 2 – variant 2; parameter 3 – variant 3 (**Table 3**).

Table 3. Values of indicators for finding the optimal solution using the heuristic algorithm (Example 2)

	i	**1**	**2**	**3**	**4**	**5**	**6**	***i***	**1**	**2**	**3**	**4**	**5**	**6**	$\sum_{i=1}^{6} R_i$	C^{opt}, **€/h**
	$M[\tau]$, min.	6														
	λ_i	10,0	4,0	4,0	2,0	6,0	4,0									
	t_i, min.	6	7	7	8	9	10									
	μ_i	10,0	8,571	8,571	7,5	6,667	6,0									
	$\frac{\lambda_i}{\mu_i}$	1,0	0,4667	0,4667	0,2667	0,9	0,6667									
K=1	ρ_i	0,5	0,4667	0,4667	0,2667	0,9	0,6667	R_i	2	1	1	1	1	1	7	7,18
K=2	ρ_i	0,5	0,4667	0,4667	0,2667	0,45	0,6667	R_i^{opt}	**2**	**1**	**1**	**1**	**2**	**1**	**8**	**6,33**

Example 2: Parameter 1 – variant 1; parameter 2 – variant 3; parameter 3 – variant 3 (**Table 4**).

Table 4 Values of indicators for finding the optimal solution using the heuristic algorithm (Example 3)

	i	1	2	3	4	5	6	i	1	2	3	4	5	6	$\sum_{i=1}^{6} R_i$	C^{opt}, €/h
	$M[\tau]$, min.	4														
	λ_i	15,0	6,0	6,0	3,0	9,0	6,0									
	t_i, min.	8	9	9	10	11	12									
	μ_i	7,5	6,667	6,667	6,0	5,455	5,0									
	$\frac{\lambda_i}{\mu_i}$	2,0	0,9	0,9	0,5	1,6499	1,2									
K=1	ρ_i	0,6667	0,9	0,9	0,5	0,8249	0,6	R_i	3	1	1	1	2	2	10	8,11
K=2	ρ_i	0,6667	0,45	0,9	0,5	0,8249	0,6	R_i	3	2	1	1	2	2	11	7,25
K=3	ρ_i	0,6667	0,45	0,45	0,5	0,8249	0,6	R_i^{opt}	**3**	**2**	**2**	**1**	**2**	**2**	**12**	**6,40**

It is easy to see that the proposed heuristic algorithm for solving problem (12) turns out to be very simple to implement. The verification of this algorithm for the specified above 27 options (**Table 1**) for combining the values of the parameters of the process of distribution center functioning shows that the number of calculations of the objective function using the heuristic method is no more than 0.35% of the number of calculations of the objective function with full enumeration, when the number of possible solutions (the number of combinations C_{12}^{6}) is 924. The authors do not claim that the proposed heuristic method always gives the optimal result. But the calculations performed within the framework of this problem with the dimension of up to N = 20 units showed that the optimal solutions obtained using this method do not differ from the optimal solutions obtained by the exhaustive search method, which allows us to assert its accuracy.

5. DISCUSSION

The use of the proposed heuristic method makes it possible to study changes in the values of the main indicators determined in this task, with different options for the values of the parameters of the process of functioning of the distribution center, which are given in **Table 1**.

The dependences of the obtained minimum total costs for servicing cargo flows by forklifts per unit of time on different values of the intensities of the arrival of goods and their service, taking into account different schemes of cargo processing in the distribution center, are shown in **Figure 4**. The values of the reduced minimum total costs of servicing goods by forklifts in the DC per unit of time are obtained for the ratio of operating costs for maintaining the forklift and specific losses associated with the stay of cargo units in the queue for service, $C_{fm}^{1} / C_q = 3/1$.

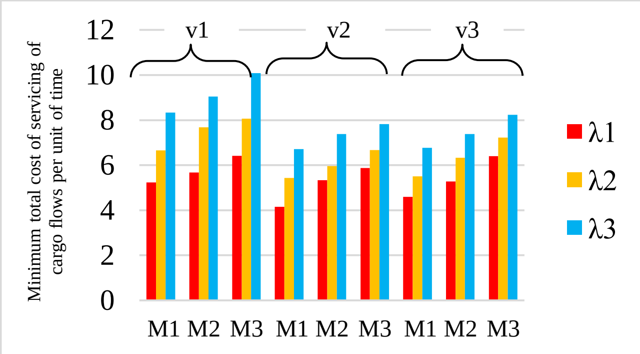


Figure 4 Minimum total cost of servicing forklifts of cargo flows per unit of time for different values of the intensities of goods arrival and their servicing for different schemes of cargo handling in the distribution center

The dependences of the optimal number of forklifts corresponding to the above values of the minimum total costs of service, on different values of the intensities of goods arrival and their service, taking into account different schemes of cargo handling in the DC are shown in **Figure 5**. The values of the shown optimal number of forklifts are also derived from the ratio of costs $C_{fm}^{1} / C_q = 3/1$.

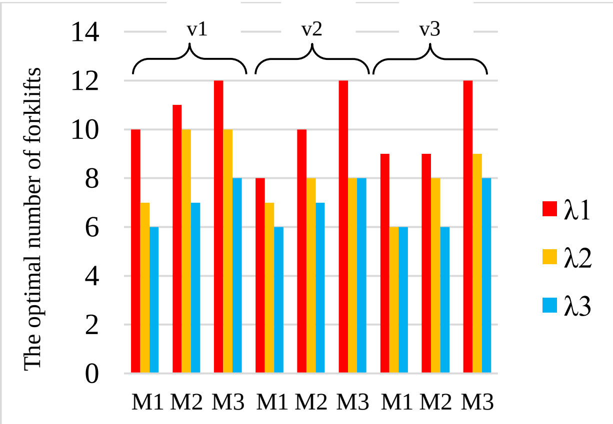


Figure 5 The optimal number of forklifts for different values of the intensity of goods arrival and their service for different schemes of cargo handling in the distribution center

Based on the data obtained in **Figures 4** and **5**, we can conclude that the minimum total costs of servicing cargo flow per unit of time, with the increase in the intensity of goods arrival at the DC and the given level of freight servicing intensities in the technological zones of the warehouse system, decrease for by increasing the number of forklifts. The minimum total maintenance costs and the optimal number of forklifts, with the same values of the intensity of goods arrival at the distribution center, increase with the decrease in the intensity of cargo handling in the technological areas of the warehouse system. Higher values of the minimum total costs of maintenance and the optimal number of forklifts, with the same values of the intensity of goods arrival at the DC and the intensities of cargo servicing in the technological areas of the warehouse system, were obtained for cargo processing schemes: service with temporary storage of goods dominant and service with multi-stage cross-docking dominant, which is explained by the large number of stages in the processing of cargo flows in these scenarios of the distribution center.

The calculated optimal number of forklifts in each technological area of the DC for different variants of the values of the parameters of the distribution center operation at the cost ratio $C^{1}_{\text{fm}} / C_{\text{q}} = 3/1$ shown in **Figure 6**.

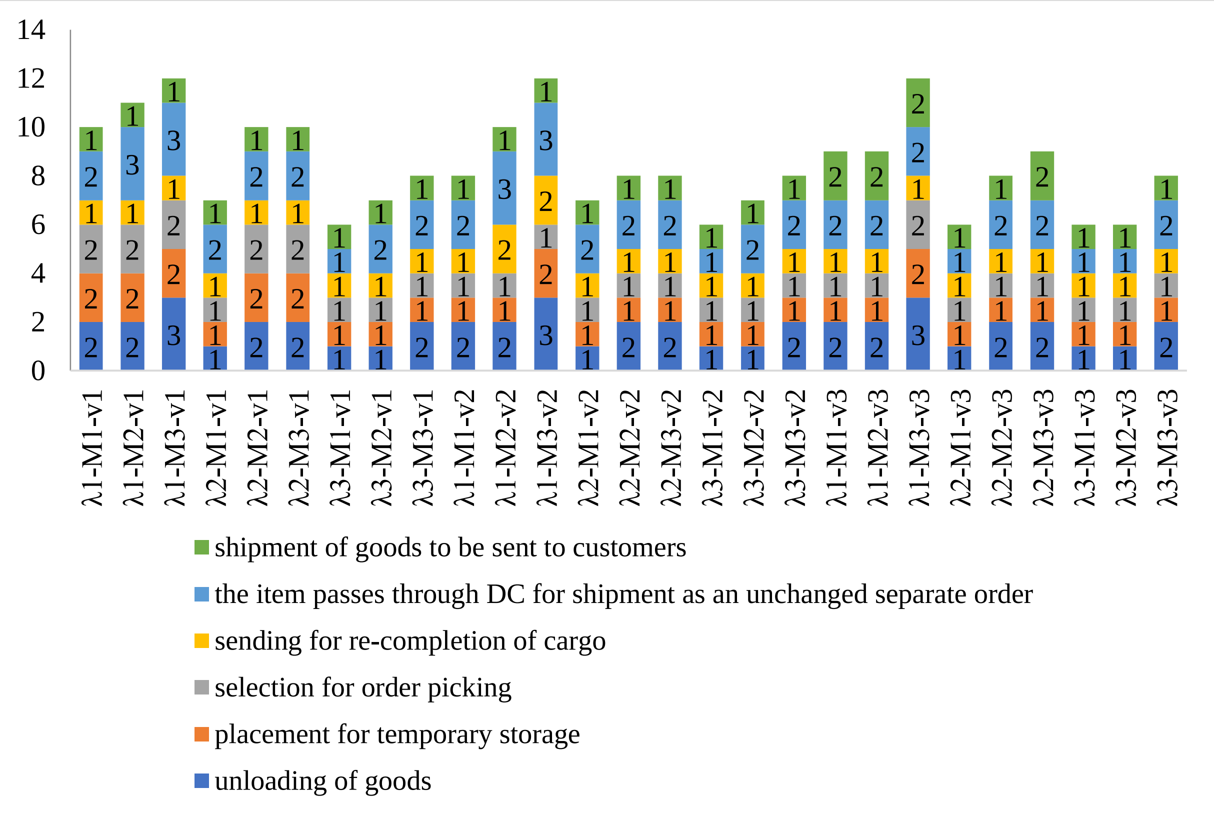


Figure 6 The optimal number of forklifts in each technological area of the distribution center for different values of the intensities of the arrival of goods and their service for different cargo handling schemes

Analysis of the data shown in **Figure 6** makes it possible to determine the average values of the number of forklifts both in the DC as a whole and in each of its technological areas. Of greatest practical interest is the distribution of forklifts by technological areas of the distribution center, depending on the level of intensity of cargo servicing (**Table 5**).

Table 5 Distribution of Forklifts by Technological Areas of the Distribution Center

Level of Intensity of Cargo Servicing	Average Value of the Total Number of Forklifts in DC	Average Values of the Number of Forklifts in the Technological Areas of the Distribution Center					
		Unloading of Goods	Placement for Temporary Storage	Selection for Order Picking	Sending for Re-Completion of Cargo	The Item Passes through DC for Shipment as an Unchanged Separate Order	Shipment of Goods to be Sent to Customers
M1	7,22	1,33	1,11	1,11	1,0	1,56	1,11
M2	8,44	1,67	1,22	1,22	1,11	2,11	1,11
M3	9,67	2,33	1,44	1,33	1,11	2,22	1,22

The obtained average values of the number of forklifts allow us to determine the most loaded technological areas of the distribution center, as well as to select models of forklifts of different capacities for their distribution among the technological zones in accordance with their load.

Figure 7 demonstrates the dependencies of the minimum total costs of servicing cargo flows by forklifts per unit of time on different values of the intensities of goods arrival and their service, considering different schemes of cargo processing in the DC for different options for the ratio of operating costs for forklift maintenance and specific losses associated with the presence of cargo units in the queue for service, $C_{\text{fm}}^{1} / C_{\text{q}}$.

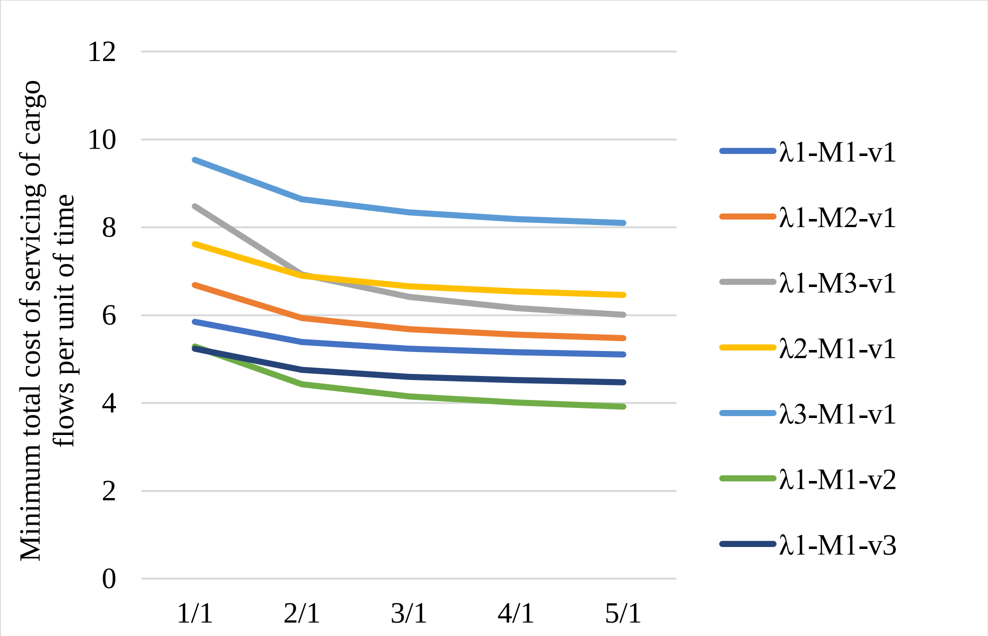


Figure 7 Dependences of the minimum total costs of servicing cargo flows by forklifts per unit of time on different options or the ratio of operating costs for maintaining the forklift and specific losses associated with the stay of cargo units in the queue for service

There is an obvious general tendency to reduce the minimum total costs of service with the increase in the ratio of operating costs for maintaining the forklift to specific losses associated with the stay of load units in the queue for service. The sharper decrease in the minimum total cost of service is observed with high penalties for late service of cargo units (options 1/1, 1/2, 1/3). At the same time, the rate of decrease in the minimum total costs for these variants of the ratio is more significantly influenced among the parameters under consideration by the intensity of cargo servicing in the distribution center.

6. CONCLUSION

Mechanization and the need to maintain the stable productivity of warehouse complexes of distribution centers requires the creation of tools for modelling their functioning, which would reflect the operation of mobile material handling equipment, the amount of which determines the logistics costs and time for performing warehouse operations for processing goods passing through such centers. The streaming nature of the functioning process and the multivariance of the schemes for servicing cargo flows in the DC led to the use of the open queuing network model to solve the problem of determining the optimal number of forklifts. Optimization is carried out according to the criterion of minimizing the total costs of servicing cargo flows per unit of time, including the costs of maintaining forklifts and the costs of handling cargo flows in the distribution center. The proposed mathematical model takes into account the critically important parameters of the distribution center functioning process: the intensity of goods arrival, the intensity of servicing the loading units by forklifts, the main technological areas, different cargo handling schemes, the operating costs of maintaining the forklift, and the specific losses associated with the stay of loading units in the queue for service. In view of the complexity of the application of classical optimization methods for solving this problem, the heuristic algorithm has been developed that allows in the short time to determine the optimal number of service channels in large-scale open queuing networks.

The article presents the simulation results for different operating modes of the distribution center, which are determined by the options for the values of the selected parameters, reflecting the high, medium, and low levels of complexity of the functioning process for three typical schemes for servicing the cargo flows of the DC under study. The values of the minimum total costs for servicing cargo flows in the DC and the optimal number of forklifts in its technological areas are obtained for different combinations of the values of these parameters.

The proposed mathematical model makes it possible to develop management decisions aimed at increasing the efficiency of the functioning of distribution centers, as well as to reduce investment in their technical development.

Further developments will be devoted to applying the presented approach to optimizing the amount of transport and warehouse equipment to ensure the efficient operation of participants in logistics supply chains in large geographically distributed retail chains with several distribution centers.

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