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COMPUTER MODELING OF WAREHOUSE LOGISTICS PROCESSES: TECHNOLOGY OF RATIONAL SLOT SELECTION FOR PICKER'S ROUTE MINIMIZATION

The article is devoted to solving scientific and practical problems of increasing the efficiency of logistics systems by minimizing the duration of material handling equipment (MHE) routes using the example of picking orders in warehouses with shared storage. The order picking process is one of the most labor-intensive and expensive operations, as the movement of staff or machinery accounts for over 50 percent of the total picking time. When goods are scattered throughout the warehouse, an additional problem arises regarding the rational selection of slots for picking goods in accordance with the order. To ensure the rational selection of locations, the PIV (Proximity Indexed Value) multi-criteria decision-making method was applied in this study. The locations of a particular item are considered as alternatives, each characterized by different criteria. Three criteria have been selected. To evaluate the alternatives (slots) according to the criterion 'degree of satisfaction of demand for other items in the order', it is proposed to take into account the potential of adjacent locations.

A hypothesis has been formulated regarding the impact of sorting goods within orders for the subsequent application of the PIV method. A heuristic for the preliminary ranking of items within orders has been justified and proposed, based on the scarcity of alternative locations in the warehouse, thereby implementing the principle of 'limited choice'. To verify the hypothesis, a three-dimensional simulation model of the goods storage area of the sorting center with a capacity of 360 unique slots was developed. Computer modeling in the MATLAB environment allowed us to recreate the topological labyrinth of the warehouse, record the coordinates of the aisles between racks and the operational routes, and ensure that virtual equipment moved strictly along the center lines of the aisles via designated access points. As part of experimental research, a comparative analysis of route construction using the nearest neighbor algorithm for two scenarios was performed: classical processing of the consignment note "top-down" and processing according to the proposed principle of "limited choice". The results of a series of computer experiments for order waves of 5 to 15 items confirmed the validity of the hypothesis and showed a reduction in the total duration of the material handling equipment route by 2–9% when processing an order according to the principle of limited choice.

Keywords: warehouse logistics, rational choice, choice constraints, computer modeling, multi-criteria decision making, PIV method.

Introduction

In recent years, the retail sector has been undergoing structural transformation [1]. Before the paradigm shift in retail led to the growth of e-commerce, which in turn has attracted significant attention to warehouses, which have become the main customer fulfillment centers today. One way to achieve a competitive advantage for a company is to improve the functioning of all processes, including warehouse operations. Optimizing warehouse fulfillment processes is becoming crucial for the company's efficiency, competitiveness, and customer satisfaction.

The order fulfillment process involves searching for and retrieving specific items from the warehouse based on customer orders. Achieving the desired level of customer service at minimal cost requires continuous improvement of working methods, technologies and warehouse management strategies and becomes the main goal of warehouse management systems [2,3].

Although companies are increasingly paying attention to automation of the processes of placing and collecting goods in

warehouses, however, many companies, especially small and medium-sized enterprises, still prefer a "person-to-product" system ("picker-to-product"), in which a warehouse worker, moving along the aisles, picks goods according to the order. Companies use manual order picking because of the high variability of demand and the flexibility of people to changes in the order picking process [4]. K. Dmytrow notes that 60% of companies still use classic manual order picking systems [5]. However, even classic manual order picking systems are constantly improved through the use of material handling equipment (MHE). E-commerce warehouses often combine two approaches to order fulfillment.

Rational order picking technology and reducing costs for this warehouse operation are a priority for many companies due to the fact that the order picking process is one of the most time-consuming and expensive in the warehouse. The order picking process can reach, according to various estimates, up to 55–75% of all labor costs in the warehouse [6,7].

Optimizing the picking process leads to reduced costs for businesses. Therefore, the attention of scientists and companies to improving the order picking process is constantly growing.

In the "picker to product" scheme, the process of completing includes: moving around the warehouse, searching for goods, removing goods from storage locations, and organizational activities. Among all the activities related to picking orders, the picker's movement takes up the largest part of the time, which is 50-55% of the total order picking time [7,8]. Therefore, significant attention of researchers is directed at reducing travel time of picker, i.e. building an optimal picker's travel route.

Before building a route that the picker must follow, it is necessary to determine the places that need to be visited (route points). And this depends on the method of storing goods in the warehouse. There are two main storage methods: dedicated storage and shared storage. In dedicated storage, a certain product is stored in only one place, in other words, the specified place is designated only for storing a certain product. In the case of shared storage, a certain product can theoretically be stored in several places. Shared storage provides much better use of storage space, but in this case the product is "dispersed throughout the warehouse" [7].

Many modern companies, especially e-commerce warehouses, use shared storage, also called the mixed-shelf concept or distributed storage. As M. Schiffer et al. [9] point out, this storage method increases the likelihood that items ordered together will be located nearby somewhere in the warehouse.

In the case of shared storage, an additional problem of choice arises: from which places should the necessary goods be taken [1,5]. To optimize the route, it is important that the places that need to be visited during order picking are as close to each other as possible. As noted K. Dmytrow, the problem of choosing locations in shared storage systems is little considered by scientists [5].

Literature review

Warehouse operation and management as an important area of research has been relevant for a long time and remains relevant today.[7]. Warehouse processes are a set of operations related to receiving, storing, picking and shipping products. The implementation of these processes can take place according to different strategies. The attention of companies to effective warehouse operations is constantly growing. Therefore, numerous studies concern various aspects of improving warehouse processes. Most researchers point out that the key to improving the efficiency of warehouse operations is optimization order picking process. Over the past decades. Much research has been conducted on improving the order picking process, but managing this process remains challenging.[7]. Also, there is still a gap between real practice and scientific research. Modern requirements for increasing the efficiency of warehouse operations require new improved methods and algorithms. Many algorithms developed by scientists cannot always be applied in real warehouse conditions and need adjustment and improvement.

The majority of academic research focuses on storage allocation strategies, order bundling problems, and the picker routing problem.

The problem of storage space allocation is addressed, in particular, in the work of I. Çobanoğlu and others [10]. Xu, X. and Ren, C [11,12], Albán et al. [13]. The problem of order packaging is considered, in particular, in the works of Esra Boz and Nil Aras [14, 15], A. Eydi et al. [16].

Many scientists combine these tasks in their research. So X. Feng and X. Hu [17] solved the problem of jointly optimizing order packaging and minimizing the total order fulfillment time. Kubler P. et al. [18] considered the problem of simultaneous optimization of storage, packaging and routing. Silva A. etc. [19] considered the integration of storage location and order picking issues. Simultaneous optimization of storage utilization and minimization of movement time were considered in their work by Fontana et al. [20]. Bolaños-Zuñiga et al. [8] presented in their work a review of works related to the combination of the storage location assignment problem and the routing problem.

However, scientists pay most attention to the problem of constructing the optimal route for the picker. Choosing the optimal path for the picker to move ensures increased productivity in the order picking process.

Researchers have developed various approaches to solving the warehouse routing problem, aimed at minimizing the distance and travel time of workers during order picking. Exact methods, heuristics have been proposed [11,12, 21,4], metaheuristics [19,5], genetic algorithms [22,23,24,25] and stochastic models [23, 26].

H.D. Ratliff and A.S. Rosenthal in 1983, using graph theory and dynamic programming, developed an exact algorithm that allowed solving the problem of optimizing the picker's route for a single-block rectangular warehouse. This algorithm provides an optimal solution for warehouses with any number of parallel aisles and two main aisles. K.J. Roodbergen and R. De Koster later generalized the algorithm of H.D. Ratliff and A.S. Rosenthal to the case of warehouses with two blocks (three main aisles). For other types of warehouses, finding the shortest path is a more complex and time-consuming task [27,7]. In practice, optimal approaches to the routing problem are not often used. This is primarily due to their high computational complexity. It is also worth noting that the optimal algorithm is not available for every warehouse layout. And optimal routes may seem illogical to workers picking orders, who as a result deviate from the specified routes [7,5].

In practice, the order picker routing problem is often solved using heuristic methods that allow achieving solutions close to optimal ones. Heuristic methods are a popular area of research in warehouse operations due to their simplicity and ease of implementation. However, their performance usually depends on the specific parameters of the particular warehouse they are applied to. The most common heuristic methods are S-Shape, Midpoint, Return, Largest gap, Combined.

Many studies have been devoted to comparing heuristic methods with each other or comparing heuristic methods with other approaches to the problem of picking routing. In particular, Esra Boz and Nil Aras [14] compared the results of applying heuristic algorithms. Cipto Purwanto et al. [28] compared the distance traveled by pickers in the current state (without a specific method) with the optimization results obtained using heuristic methods.

Heuristic methods have also been used, in particular, in the works of X. Feng and X. Hu [17], O. Kucheruk and I. Drach [7], Cipto Purwanto and Rienna Oktarina [28], T. Engels et al. [4], R. Puka and others [29], Y. Z. Zeng et al. [25].

In modern research picker routing problems one of the main approaches is to use a genetic algorithm [25]. Often, genetic algorithm is used in combination with other methods in research. In particular, X. Feng and X. Hu [17] used genetic algorithm and heuristic method in their research. Fontana et al. [20] proposed a hybrid approach based on multi-objective genetic algorithm and multi-criteria decision making.

It is worth noting that the problem of rational selection of locations (slots) for storing goods that the picker should visit has received little attention from scientists. In particular, this problem is considered in the works K. Dmytrow [5, 30], where he suggests applying methods multi-criteria decision making.

Purpose of the article

Research objective is to develop an approach to rational selection of slots for minimizing the length of material handling equipment (MHE) routes in warehouse logistics systems with shared storage.

Methodology

Order picking is one of the most important operations in a warehouse. Therefore, warehouse work should be organized in such a way as to optimize the time for picking orders. One of the factors affecting warehouse efficiency is the problem of determining effective routes for pickers. The length of the picker's route primarily depends on the selected routing method, the size and configuration of the warehouse. The goal of routing in a warehouse is to find the shortest path.

Building a route begins with determining the route reference points, i.e. the storage locations that the picker needs to visit. In the case of shared storage of goods, a certain product may be located in several locations. Therefore, it is necessary to decide from which location to pick a certain product from the list of equipment.

In this case, we can consider the locations of a certain product (slots) as alternatives, which are characterized by different criteria. To select the best alternative, multi-criteria decision-making methods can be used. For example, K. Dmytrow in his research [5] to select locations uses COPRAS method.

In this study, we propose the use of the PIV method, which was created in 2018. The advantage of this method is to minimize the phenomenon of rank shifting, where the rankings of alternatives change when one or more alternatives are added to the created list of alternatives to be ranked. Due to this advantage, this method is actively used for ranking solutions in many different industries [31].

The steps of the PIV method can be described as follows [31,32].

Let n be the number of criteria by which alternatives are evaluated, and m be the number of alternatives.

Step 1. Building a decision matrix:

$$X = [x_{ij}]_{m \times n} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (1)$$

where A_i , ($i = 1, 2, \dots, m$) are alternatives, C_j , ($j = 1, 2, \dots, n$) are criteria by which alternatives are evaluated, x_{ij} – evaluation of the i -th alternative according to the j -th criterion.

Step 2. Constructing a normalized decision matrix using equality

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (2)$$

Step 3. Construction of a weighted decision matrix:

$$v_{ij} = n_{ij} \cdot w_j \quad (3)$$

where w_j is the weight of criterion j .

Step 4. Estimating the weighted index of proximity to the best solution

$$u_{ij} = \max_i v_{ij} - v_{ij}, \text{ for benefit criteria;} \quad (4)$$

$$u_{ij} = v_{ij} - \min_i v_{ij}, \text{ for cost criteria.} \quad (5)$$

Step 5. Determining the overall proximity value.

$$d_i = \sum_{j=1}^n u_{ij}. \quad (6)$$

Alternatives are arranged according to the principle that the best alternative is the one with the lowest value. d_i .

The attractiveness of a location (slot) from the point of view of a certain type of product depends on its distance from the start (the place of receipt and delivery of the order), on what part of the order for this product we can satisfy in this slot, and also on how close this slot is to the slots in which there are other products from the order. Therefore, to select a slot, we chose the following criteria: C1 - distance from the start; C2 - the degree of satisfaction of demand for the product according to the order; C3 - the degree of satisfaction of demand for other products from the order that can be collected in a certain vicinity of this slot.

Criteria C2 and C3 are benefit criteria, and criterion C1 is a cost criterion.

The distance from the start can be measured in different units, in particular, the unit of measurement can be the width of the racks. K. Dmytrów [5], for example, suggests using Manhattan distance with the unit of measurement "rack width".

In this study, as a metric, which defines the distance between two points, the Manhattan distance is used.

The degree of satisfaction of demand for goods according to the order is proposed to be described by the indicator ρ , which shows the ratio of the available quantity of the product in the slot to the remaining demand for the order, it is clear that $\rho \leq 1$.

This indicator is calculated as follows [33, 5]:

$$\rho = \begin{cases} \frac{k}{z}, & \text{if } z > k \\ 1, & \text{otherwise} \end{cases}, \quad (7)$$

where k is the number of units of a particular product in a given slot, z —current demand for this product in the order (how many units of the product are specified in the order or remain in the order after the method iteration).

Each product has a unique SKU (Stock Keeping Unit) identifier, which is used for inventory accounting, storage, and inventory management in a warehouse. Typically, the degree of satisfaction of demand for other products according to an order that can be assembled in a certain vicinity of this slot is implemented as a simple binary counter: the algorithm looks for how many useful SKUs lie within radius R and returns an integer [v5]. We offer as a way to satisfy the demand for other goods according to the order that can be collected in a certain vicinity of this slot, calculate as the potential of adjacent locations, defined by the formula:

$$v = \frac{\rho_1 + \rho_2 + \dots}{s} \quad (8)$$

where t is the number of slots that fall into the given neighborhood R , s — the number of items of the product range included in the order.

If, for example, within a radius of R meters there is a desired product, but there is only 1 of it, and 50 are needed, the classical approach would still count it as a full-fledged "useful neighbor". According to approach (8), $\rho = 1/50 = 0.02$ will be calculated for this slot, the contribution of this slot to the attractiveness of the zone will be negligible if there are no products of the same nomenclature nearby. The loader will not go to a location where there are "leftovers" that do not save the order. Instead, it will choose a zone where neighbors have greater potential.

The neighborhood can be defined in various ways, in particular, it can be slots located in the same alley as the given slot, or those slots located at a Manhattan distance less than R from a given slot.

When viewing an order, we select a product from the list. This product is presented in several candidate slots, and they will be alternatives. However, the question of which product to choose first remains open.

After applying the PIV method and selecting the first storage slot, the volume of goods to be removed from this location is determined. The current order is updated by reducing the required quantity of goods by the amount provided by the selected slot. The warehouse status is updated accordingly.

After that, the PIV method is used again to select the next slot. IterativeThe process continues until the demand for all items in the order is fully satisfied and all items in the order will not become zero.

After determining a complete list of necessary (reference) slots, corresponding points are built in the access alleys - places where the MHE moves. The next step. The nearest neighbor path construction algorithm is used.

In their research K. Dmytrow paid much attention to the issue of weighting factors for the selection criteria of reference slots. His research proved that the values of weighting factors have an impact on the selection of reference slots [30]. Our study used weighting factors agreed with expert practitioners, namely $w_1=0.4$, $w_2=0.2$, $w_3=0.4$. However, in our opinion, the choice of product in the order, from which the application of the multi-criteria decision-making method will begin (in particular, PIV method), also affects the construction of the picker's optimal route.

The strategy of ordering and selecting target Stock Keeping Units (SKUs) from the general order list at each iteration of the PIV algorithm significantly affects the spatial concentration of picking points and the final length of the picking route. It is assumed that dynamically selecting initially those products that have the fewest alternative storage locations in the warehouse allows you to fix the necessary route control points at the early stages. In our opinion, this minimizes the risk of trajectory dispersion at the end of the picking wave and ensures a reduction in the route length in the traveling salesman problem. A number of experiments were conducted to confirm this hypothesis.

Presentation of the main research material

To conduct experimental research, a simulation model of a three-dimensional warehouse of a sorting center was developed. In this work, computer simulation modeling tools implemented in the MATLAB computing environment (version R2023a) were used.

The object of the study is the storage area of piece goods of the sorting center, which is presented in the form of a three-dimensional rectangular coordinate grid with overall dimensions: length 19.2 m, width 30.0 m and usable height 6.0 m. The warehouse area is divided into two symmetrical blocks, which are separated from each other by a horizontal traffic highway. Each block contains three lines of double racks. The coordinates of the rack lines along the X axis are rigidly fixed at the marks: [0; 5.2; 6.4; 11.6; 12.8; 18.0] meters. Each individual rack has a length of 9.0 m and a width of 1.2 m. Each rack is divided into 6 equal structural sections along its length. The length of one section is 1.5 m. The image of the warehouse (top view) is shown in Figure 1.

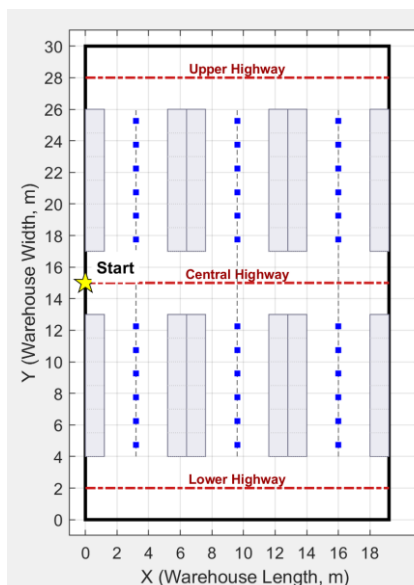


Figure 1– 2D model of the warehouse

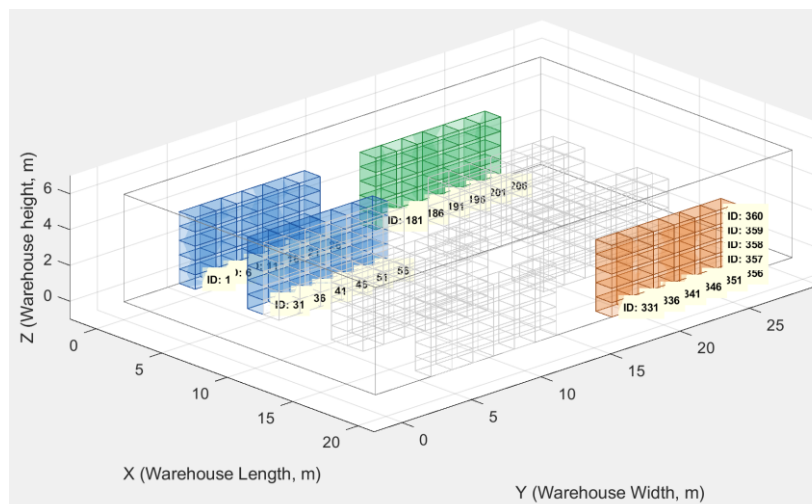


Figure 2 –3D warehouse model showing the slot indexing scheme

The rack is divided into 5 tiers of shelves in height. The height of one tier is 0.8 m. Thus, one section on one tier forms a unique slot with physical dimensions of $1.2 \times 1.5 \times 0.8$ meters. The total capacity of the warehouse is:

$$2 \text{ blocks} \times 6 \text{ shelves} \times 6 \text{ sections} \times 5 \text{ tiers} = 360 \text{ storage slots.}$$

To ensure the unhindered movement of MHE or pickers, two connection systems are provided: horizontal technological highways and vertical aisles. Horizontal technological highways consist of three through routes running parallel to the X axis (buffer zones near the walls at a distance of 2 meters from the boundaries) and one central separating highway. Vertical aisles are three inter-rack aisles oriented along the Y axis. The central axes of these aisles

are located at coordinates $X = [3.2; 9.6; 16.0]$ meters. Each such aisle serves two adjacent rows of racks (to the left and right of the picker).

To identify the locations from which to collect items from the selection list, we need to distinguish them in some way in order to apply the selection strategy. The identification of slots for real warehouses may be different, but it does not affect the essence of the study, so end-to-end numbering is used, as shown in Figure 2.

Numbering of slots starts from the bottom tier of the section and goes up to the 5th tier. After all 5 tiers of the first section are numbered, we move on to the next section of the rack (along the Y axis). When one rack is completely numbered (30 slots), we move on to the next rack by the X coordinate. First, we completely number the rack block located between the central and lower trunk, then, using the same principle, we number the cells of the racks located between the central and upper trunk.

The simulation of real warehouse processes was based on the principle of random storage, i.e. each product is randomly assigned a place in the warehouse. This storage policy is widely used in practice because it is easy to use, requires less space than other storage methods, and improves the utilization of all aisles [4]. Also, the number of goods in each slot is randomly indicated. Information about the initial location of goods in the warehouse (Fig. 3) has the form of a table with the following fields: cell number, product number, number of units of a given product in a given cell.

Cell_ID	SKU_ID	Qty
1	79	14
2	51	42
3	56	19
4	64	49
5	10	54
6	25	27
7	62	16
8	31	49
9	77	26

Figure 3 - Fragment of information regarding the initial warehouse occupancy

An order arrives at the warehouse, which looks like a list of goods with the quantity of each item, for example, as in the figure 4a. The initial order with the number of locations where the goods specified in the order are stored and their list is shown in Fig. 4b.

SKU_ID	Qty	SKU_id	Qty	Number_of_cells	List_of_cells
31	18	31	18	7	[8, 74, 175, 256, 292, 329, 357]
5	25	5	25	2	[49, 76]
52	36	52	36	6	[123, 162, 267, 283, 330, 354]
25	32	25	32	2	[6, 50]
40	16	40	16	4	[20, 64, 95, 289]
91	14	91	14	7	[32, 53, 89, 126, 238, 318, 320]
87	21	87	21	3	[44, 172, 337]
12	36	12	36	6	[119, 158, 226, 264, 317, 324]
55	31	55	31	9	[24, 41, 42, 151, 163, 202, 254, 265, 316]
33	29	33	29	5	[59, 115, 146, 230, 348]
65	14	65	14	2	[347, 349]
47	12	47	12	5	[105, 157, 197, 213, 306]

a) Initial order

b) Storage locations for the initial order

Figure 4 – Initial order information

Figure 5 shows the warehouse configuration., where all slots containing products from the order are highlighted in gray:

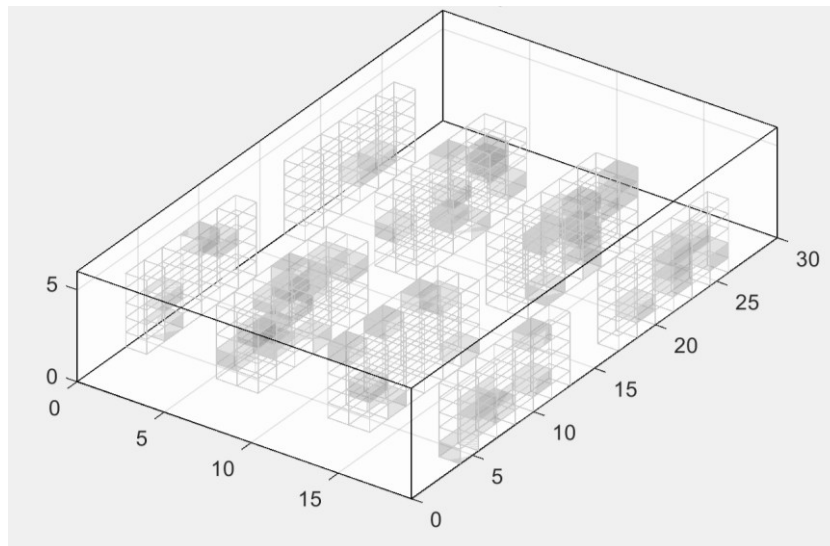


Figure 5 – Initial locations of goods from the order

Experiment 1 – Top-down order processing. According to the simulation, item 31 is the first in the list of items in the order. It is required in the amount of 18 units. In the model of our warehouse, item 31 is contained in various quantities in slots 8, 74, 175, 256, 292, 329, 357, with some slots having sufficient quantities, while others have less.

To form a set of slots that ensure the fulfillment of the order, the PIV method is applied for each SKU in the order. Thus, the iterative application of the PIV method provides a step-by-step formation of a set of locations for further route construction (Fig. 6).

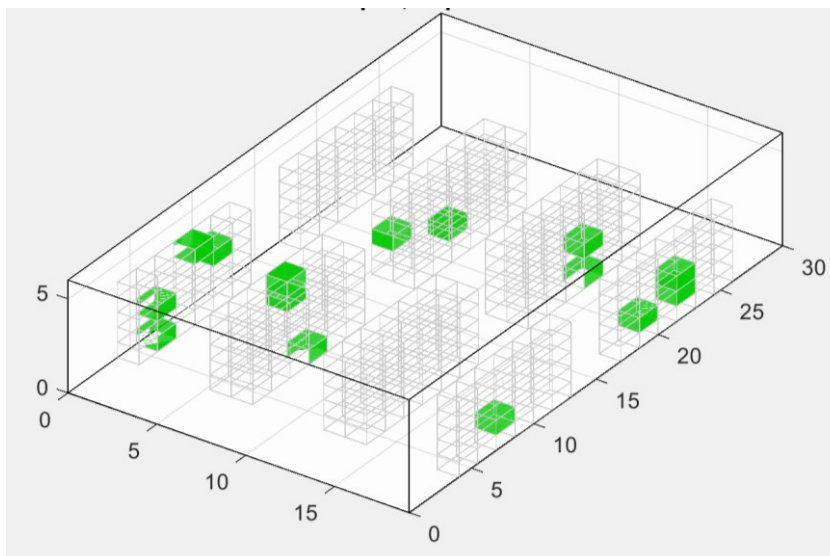


Figure 6 – 3D warehouse model with selected target slots

A feature of the model is that the picker does not drive up directly to the rack. Each of the 360 slots has its own access point on the center line of the nearest vertical aisle exactly in the middle between the racks. Further solution of the traveling salesman problem is carried out precisely according to the coordinates of these access points. This allows you to simulate the real movement of equipment strictly along the centers of the aisles. Such points are shown in Fig. 7.

The starting point of the route, from which the picker starts moving and where he returns after completing the picking wave, is located on the left border of the warehouse at a point with coordinates $X=0$; $Y=15.0$ m, which corresponds to the exit to the central highway. In the figures, it is marked with a star.

The nearest neighbor algorithm was chosen for route construction because it is characterized by simplicity of implementation, low computational complexity, and high speed [34]. The resulting route, indicating the order of traversing access points, is shown in Figure 8. The length of the constructed route is 103.1 m.

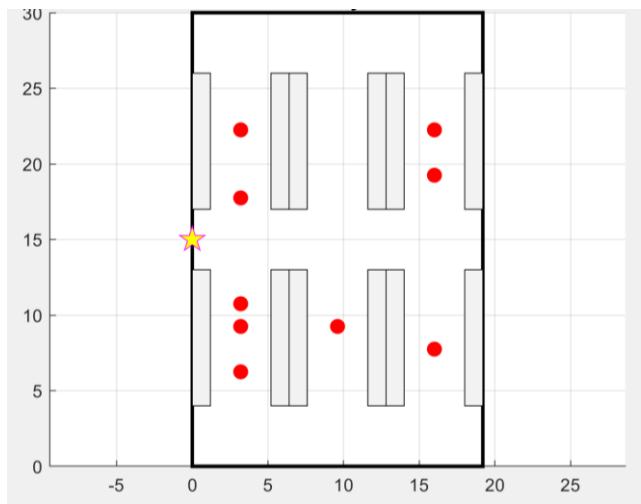


Figure 7 – Access point visualization

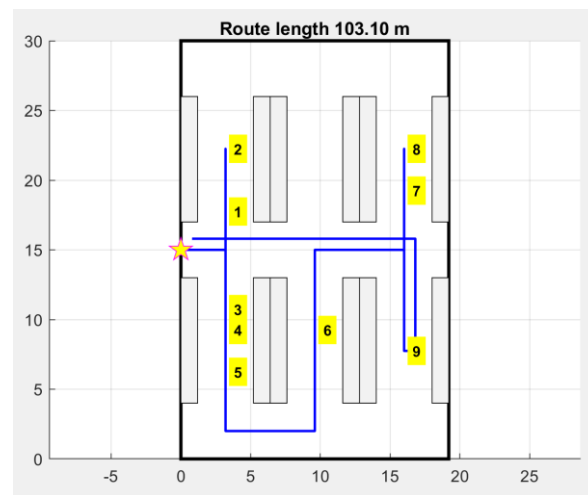


Figure 8 – Visualization of the picker's movement trajectory

Experiment 2 – Order processing based on the principle of “limited choice”. First, the order is sorted from the most scarce items in the warehouse (found in fewer locations) to those with many storage locations. According to the simulation, item 5 is found in only two locations and occupies the first position in the sorted order (Figure 9). Sorting of items with the same number of storage slots is done according to the lexicographic principle.

SKU_id	Qty	Number_of_cells	List_of_cells
5	25	2	[49, 76]
25	32	2	[6, 50]
65	14	2	[347, 349]
87	21	3	[44, 172, 337]
40	16	4	[20, 64, 95, 289]
33	29	5	[59, 115, 146, 230, 348]
47	12	5	[105, 157, 197, 213, 306]
12	36	6	[119, 158, 226, 264, 317, 324]
52	36	6	[123, 162, 267, 283, 330, 354]
31	18	7	[8, 74, 175, 256, 292, 329, 357]
91	14	7	[32, 53, 89, 126, 238, 318, 320]
55	31	9	[24, 41, 42, 151, 163, 202, 254, 265, 316]

Figure 9 – Sorted order based on the principle of “limited choice”

Therefore, the PIV method in the first step is applied to SKU 5. Then, similarly to the first experiment, the PIV method was applied for the other SKUs from the order.

The results of the experiment are presented in Figures 10-12. The length of the constructed route is 96.0 m.

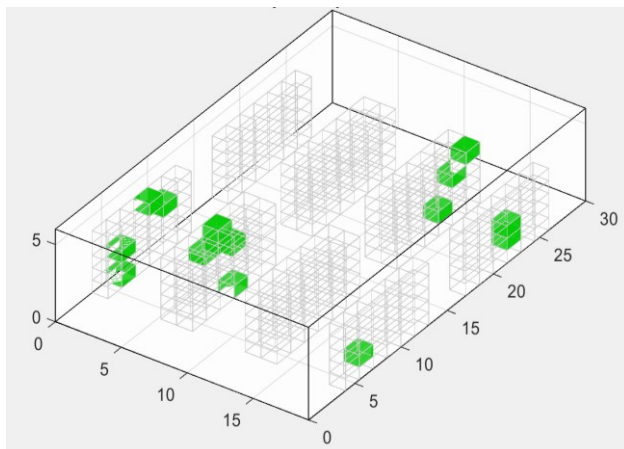


Figure 10 – 3D warehouse model with selected target slots

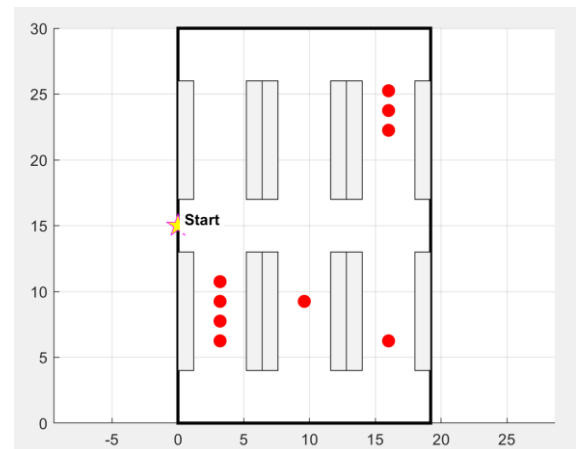


Figure 11 – Access point visualization

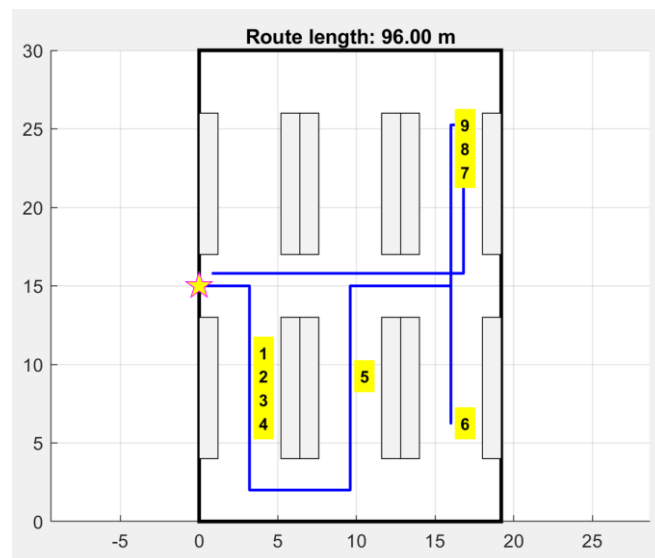


Figure 12 – Visualization of the picker's movement trajectory

The second experiment demonstrated an improvement in the route by almost 7%. Dynamic consideration of the density of useful stock in adjacent locations and preliminary sorting of the nomenclature according to the principle of "limited choice" ensured a reduction in the route length.

The results obtained confirmed the hypothesis regarding the influence of sorting of goods in the order for further application of the PIV method. In particular, the use of sorting according to the principle of "limited choice" allows you to record the necessary route control points at the early stages and minimize the risk of trajectory dispersion at the end of the picking wave, which contributed to reducing the length of the picker's route.

Conclusions

This work is devoted to solving the problem of increasing the efficiency of logistics systems using mathematical and computer models of route construction using the example of picking in warehouses with shared storage. For rational slot selection, a multi-criteria decision-making method, namely the PIV method, was applied. To evaluate alternatives (slots) according to the criterion of "degree of satisfaction of demand for other goods from the order", it was proposed to determine the potential of adjacent locations and the total capacity of the current collection wave.

A simulation model of a three-dimensional warehouse of a sorting center with a capacity of 360 storage cells with a clear coordination of access points in the inter-rack aisles was created. Computer modeling allowed to recreate the real physical limitations of the movement of MHE strictly along the centers of the aisles and technological highways.

For a random order, picker routes were constructed in two cases: processing an order without modification and processing an order sorted according to the principle of "limited choice".

The influence of the approach to order processing on the length of the picker's route is demonstrated.

A number of experiments were conducted to support the hypothesis of this study. The results of the experiments for order waves of 5 to 15 items demonstrated a reduction in the total length of the picking route by 2–9% when processing the order according to the principle of limited choice.

Prospects for further research

Prospects for further research lie in expanding the model to allow for the coordination of multiple pickers in a warehouse environment. Another area of research could be the optimization of constructed routes.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

The authors' contributions are as follows: T. Kysil determined the statistical strategy for result validation through experimental simulation waves; designed the heuristic algorithms for order sorting, developed the visualization models, and contributed to the original draft preparation and scientific editing, carried out the software implementation in the MATLAB environment; O. Kucheruk proposed the multi-criteria decision-making methodology based on the PIV method for rational slot selection, supervised the study, formulated the core research hypotheses; R. Tsalay performed the formal analysis of the warehouse logistics topological layout, carried out the 3D warehouse simulation.

DECLARATION ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE TOOLS

During the preparation of this work, the authors used Gemini for the purposes of translation, checking grammar and spelling. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ СКЛАДСЬКИХ ЛОГІСТИЧНИХ ПРОЦЕСІВ: ТЕХНОЛОГІЯ РАЦІОНАЛЬНОГО ВИБОРУ СЛОТІВ ДЛЯ МІНІМІЗАЦІЇ МАРШРУТІВ КОМПЛЕКТУВАЛЬНИКА

Стаття присвячена вирішенню науково-практичної задачі підвищення ефективності функціонування логістичних систем шляхом мінімізації довжини маршрутів підйомно-транспортного обладнання на прикладі комплектування замовлень на складах із випадковим типом зберігання (*shared storage*). Процес комплектування є однією з найбільш трудомістких і дорогих операцій, оскільки пересування працівників або техніки забирає понад 50% загального часу збору. В умовах розсіювання товарів по складу виникає додаткова проблема раціонального вибору слотів для збору товарів згідно замовлення. Для раціонального вибору локацій у роботі застосовано метод багатокритеріального прийняття рішень PIV (*Proximity Indexed Value*). Місця розташування певного товару розглядаються як альтернативи, які характеризуються різними критеріями. Обрано три критерії. Для оцінки альтернатив (слотів) за критерієм «ступінь задоволення попиту на інші товари з замовлення» запропоновано враховувати потенціал суміжних локацій.

Сформовано гіпотезу щодо впливу сортування товарів в замовленні для подальшого застосування методу РІV. Обґрунтовано та запропоновано евристику попереднього ранжування позицій у замовленнях за принципом дефіцитності альтернативних локацій на складі, що реалізує принцип «обмеженості вибору». Для верифікації сформованої гіпотези розроблено тривимірну симуляційну модель зони зберігання товарів сортувального центру місткістю 360 унікальних слотів. Комп'ютерне моделювання у середовищі MATLAB дозволило відтворити топологічний лабіринт складу, зафіксувати координати міжстелажних алей та технологічних магістралей, а також забезпечити рух віртуальної техніки суворо по центрах проїздів через виокремлені точки доступу.

У межах експериментальних досліджень виконано порівняльний аналіз побудови маршрутів за алгоритмом найближчого сусіда для двох випадків: класичного опрацювання накладної «зверху донизу» та опрацювання за запропонованим принципом «обмеженості вибору». Результати серії комп'ютерних експериментів для хвиль замовлень обсягом від 5 до 15 позицій підтвердили висунуту гіпотезу та продемонстрували скорочення загальної довжини маршруту руху підйомно-транспортного обладнання на 2–9 % при опрацюванні замовлення за принципом обмеженості вибору.

Ключові слова: складська логістика, раціональний вибір, обмеженість вибору, комп'ютерне моделювання, багатокритеріальне прийняття рішень, метод РІV.