Data processing method for cost-effective logistic activities

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Abstract

Data processing methods are now used in all areas of human activity. This is explained due to the development of information technology, the increase in the number of sensors, and the computing capabilities. Effective data processing is a key to sustainable development and provides an opportunity for improvement based on reliable decision-making. In the transport industry, the development of data processing algorithms is a major priority when improving the logistics support of the equipment life cycle. This paper discusses the process of optimizing logistics routes in order to minimize costs, increase the efficiency of the use of vehicles, their accuracy and timeliness of delivery. The paper gives three basic results. Firstly, the main stages of modeling the system of cost-effective logistics transportation of equipment are determined in order to develop effective strategies for operation. Secondly, the main requirements for the development of modern data processing methods for cost-effective logistics transportation of equipment are formed, which include indicators of accuracy, timeliness, forecasting, automation, safety and efficiency. Thirdly, a comprehensive approach to the development of a new innovative data processing method for cost-effective logistics transportation of equipment is developed, which allows obtaining the following results: reducing logistics costs; reducing equipment delivery time; increasing transportation reliability; automating and adapting logistics processes. The obtained results can be used for data processing algorithmic support improvement while optimizing maintenance and repair processes of transport equipment.

Keywords

data processing, decision-making, efficiency, predictive analytics, DBSCAN clustering, transportation, logistics activities, supply chain, logistics processes, cost analysis

1. Introduction

Data processing methods are now used in all areas of human activity. Data analytics becomes basic tool in digital era. This is explained due to the development of information technology, the increase in the number of sensors, and the computing capabilities [1]. Effective data processing is a key to sustainable development and provides an opportunity for improvement based on reliable decision-making.

Data analytics methods allow solving key problems in the production and operation of equipment [2]. In general, these methods can be divided into four groups:

- Descriptive analytics, which allows to track trends in key parameters and generate information reports.
- Diagnostic analytics, which allows to determine the causes of observed events.
- Predictive analytics, which allows to obtain future values of key parameters, predict future events and their consequences.
- Prescriptive analytics, which allows to form strategies that prevent possible future negative events and their consequences [3, 4].

In the transport industry, the development of data processing algorithms is a major priority when improving the logistics support of the equipment life cycle [5, 6].

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The transport industry plays an important role in both passenger and cargo services [7]. In today's conditions of globalization of logistics routes, digitalization of services, route optimization is of primary importance in creating a supply chain and delivering raw materials to the end consumer [8].

Transport logistics consists not only of optimizing routes, but also of controlling cargo flows using modern digital technologies, minimizing costs, planning transportation, and ensuring security [9, 10]. This is a complex process that includes transportation and control over the movement of goods, which is especially relevant in today's conditions of economic instability and war. In this context, transportation of equipment requires careful planning, the use of special security measures that would help to save all available resources as much as possible.

The formation of data processing methods for cost-effective logistics transportation of equipment is an extremely urgent task for modern enterprises. Timely and accurate information processing allows to optimize delivery routes, reduce transportation costs, and increase the productivity of logistics processes [11, 12]. In the conditions of growing competition in the market, enterprises need tools that ensure maximum efficiency in the use of resources. Proper use of data helps reduce the risks of equipment downtime and untimely delivery, which is critically important for manufacturing and construction companies. Cost optimization is ensured, customer service is improved, and effective inventory and transportation management is achieved, which ultimately contributes to achieving the strategic goals of the enterprise [13, 14].

Information processing techniques give possibility integrating data from various sources and performing their analytical evaluation to make optimal decisions [15]. The implementation of such techniques ensures increased economic efficiency of logistics through rational planning of routes and use of vehicles. In addition, data processing allows to predict possible problems and quickly respond to changes in delivery conditions [16]. This not only helps save financial resources, but also increases the reliability and quality of customer service. In modern conditions of digitalization, logistics process management becomes an important factor in the competitiveness of the enterprise. Therefore, the development of effective data processing techniques is a key element in the development of a cost-effective and adaptive logistics system.

2. Literature review and problem statement

In scientific articles by various authors, the following key features of logistics transportation optimization are highlighted, which go beyond simple cost reduction and include strategic and technological aspects. In article [17], it is determined that transport logistics management should not be limited to individual operations, but requires integration into the overall supply chain management system. In article [18], the optimization of transport processes in the logistics chain is considered, which provides a number of economic advantages, in particular, reducing costs for transport charges, storage, or production processes.

Digital technologies penetrate almost all processes and areas of economic activity. The application of artificial intelligence (AI) in logistics is no exception. Using the capabilities of AI, stakeholders in logistics can improve decision-making processes, optimize resource use and minimize environmental impact [19].

Optimization of transport routes for the purpose of cost-effective transportation of equipment should ensure transparency and accuracy of processes, which leads to better customer satisfaction due to timely and complete deliveries, as well as more efficient service [20]. The development of an optimal route allows to reduce the time of cargo on the road and the number of intermediate stops/transshipments, reducing the likelihood of damage. In the article [21], the construction of the shortest cyclic route is presented, which ensures the delivery of homogeneous cargo from manufacturers to consumers. The use of modern digital technologies of machine learning (ML), Internet of Things (IoT) can help optimize product supply chains, improve customer service, reduce risks and create new business models. Further optimization is carried out using process analysis to increase their core competitiveness [22].

The cost-effectiveness of logistics transportation of equipment depends on the cargo capacity. Delivery by small-capacity vehicles is profitable only if the vehicles are loaded close enough to their customers [23]. It is measured by the ratio of achieved results (timely delivery, quality maintenance) to the costs incurred.

The article [24] is devoted to the optimization of transport routes with a focus on the first and last mile of transportation. The problem considered by the authors can be attributed to the problems of micromobility. At the same time, the authors identified key areas that are relevant in the field of application of data analytics in this area. Among them are:

- problems of optimization and modeling of transportation systems based on fuzzy logic, reinforcement learning, and dynamic programming;
- problems of infrastructure optimization in order to reduce resource consumption and increase efficiency;
- problems of sustainable development in terms of reducing emissions of hazardous gases;
- problems of economic and social importance;
- problems of regulatory policy and documentation support.

As an indicator of efficiency, the authors of [24] chose the total transportation costs that need to be minimized. The optimization problem was solved in three stages by analyzing the asymmetric transportation problem, constructing the Euler circuit, and calculating the route based on the evolutionary algorithm. Overall, the developed approach allowed for a 19% improvement compared to known methods.

The article [25] considers a solution to the route optimization problem based on the use of a genetic algorithm and the Lin-Kernighan method. The proposed method was tested on real transportation data. As a result, the authors proved that the use of this method allows reducing emissions of hazardous substances by 54%.

The article [26] analyzes the problem of planning logistics routes without the use of geospatial services and maps. The author has performed a comparative analysis for five models, including a statistical regression approach and the use of a neural network, for estimating distance matrices based on geographical coordinates. It is proven that traditional statistical models systematically overestimate distances, while the neural network-based model shows significantly higher accuracy and better matches map-based routes. Overall, the article shows that practical route planning can be implemented without geospatial services and complete maps and with a cost-effective alternative to classical solutions.

The article [27] contains the approach to route optimization in road transport systems using machine learning methods, tested on the example of the transport corridor between Morocco and France. This approach takes into account key efficiency criteria, in particular safety, cost, and duration of transportation. The authors carried out a comparative analysis of various machine learning algorithms, in particular artificial neural networks, naive Bayesian classifier, support vector machine, and others, in order to assess their suitability for solving transportation problems. The obtained results allowed to conclude that the use of neural networks provides the highest prediction accuracy and contributes to the formation of safe routes with minimization of transportation costs and time.

Logistics planning tasks are also important in the case of improving the processes of technical maintenance and repair of various types of equipment. These tasks can be solved in conjunction with the optimization of the infrastructure of repair and service hubs [28], as well as the logistical support of the equipment life cycle based on the use of advanced information technologies [29].

The conducted analysis of the literature allows to make the following conclusions. The main indicator of efficiency when solving logistics problems is transportation costs. The criterion of efficiency is the minimum of this indicator. Logistics problems are currently solved using data processing methods, in particular, based on statistical approaches, machine learning methods, and artificial intelligence tools.

The purpose of this paper is to develop a new innovative data processing method for cost-effective logistics transportation of equipment.

3. Materials and methods

The data processing for cost-effective logistics transportation of equipment is a systematic set of operations for collecting, verifying, processing and analyzing information related to routes, cargo, vehicles, and resources of the enterprise. It includes the initial collection of data from various sources, such as GPS trackers, transport documents, warehouse systems, and internal databases. Then they are structured and verified to ensure the accuracy and reliability of the information. The next stage is data processing using algorithms for optimizing routes, distributing cargo, and planning the use of vehicles. In parallel, an economic analysis is carried out to assess costs and determine the most effective solutions. Based on the results of the analysis, a logistics transportation plan is formed, which allows minimizing costs and equipment delivery time. An important component of the process is monitoring the implementation of the plan and making adjustments in real time in case of changing conditions. The process also involves automation and integration of data to increase the speed of decision-making. The main and auxiliary logistics processes during transportation require modeling on basic digital technologies that ensure a high level of operational efficiency and the ways that the enterprise should implement to improve it [30, 31].

Due to its comprehensiveness and analytical approach, this process ensures increased economic efficiency of logistics processes. In general, it is a key element of strategic management of equipment transportation to the customer.

The main stages of modeling the cost-effective logistics transportation system for equipment are follows:

1. Data collection and integration, which is provided by the formation of a single database of information on routes, vehicles, equipment, cargo, warehouse stocks, and resources of the enterprise for further analytics.
2. Verification and checking of data, their reliability and completeness of information, elimination of errors and duplications, which ensures the reliability of models.
3. Analysis of transportation flows, identification of bottlenecks, optimization of routes, and determination of priorities for equipment delivery to reduce time and costs.
4. Forecasting of costs and resource needs, assessment of financial and material costs for equipment transportation, and forecasting of the load on vehicles and personnel.
5. Optimization of logistics processes, development of models that allow minimizing costs, increasing the efficiency of vehicle use, and reducing downtime.
6. Scenario modeling, assessment of various equipment delivery options, and response to unforeseen situations (traffic jams, weather conditions, and technical malfunctions).
7. Automation of the decision-making process, creation of algorithms that allow for rapid processing of large amounts of data and effective logistics decisions.
8. Monitoring and control of task performance, ensuring the ability to track route implementation and adjust plans in real time.
9. Increasing economic efficiency, maximizing the profitability of logistics operations by reducing equipment transportation costs and increasing productivity.
10. Development of strategic management, providing enterprise management with sound analytical data for planning the logistics system.

Logistics systems must develop effective operating strategies that will integrate all aspects of its activities, taking into account the impact of external and internal factors, as well as potential risks [32, 33].

Requirements for the development of modern data processing methods for cost-effective logistics transportation of equipment are presented in Table 1.

Modern data processing methods for the logistics transportation of equipment must ensure accuracy, timeliness, and full integration of information from various sources [34]. They must effectively analyze routes, forecast costs, and optimize the use of transport resources. Automation and analytical algorithms

Table 1
Basic Requirements for the Development of Modern Data Processing Methods for Cost-Effective Logistics Transportation of Equipments

Requirement	Description	Positive impact on the logistics process
Data accuracy	Ensuring high reliability and completeness of information about routes, cargo, and resources	Reducing the risk of planning errors, reducing losses and downtime
Timeliness	Prompt updating of information in real time	Ability to quickly respond to changes in transportation conditions
Source integration	Combining data from different systems: GPS, ERP, warehouses, transport documents	Creating a complete horizon of logistics processes, improving analysis
Analytical ability	Ability to conduct economic and route analysis, forecasting, and optimization	Increasing the efficiency of planning and resource use
Flexibility	Adapting the methodology to changes in cargo volumes, types of transport, and delivery conditions	Ensuring the continuity of logistics operations in different conditions
Automation	Using algorithms for processing datasets and making decisions	Reducing manual procedures number, accelerating planning, and reducing the risk of errors
Forecasting	Ability to model various scenarios and assess risks	Optimizing routes, reducing costs, and increasing delivery reliability
Economic efficiency	Orientation to minimize costs and maximize productivity	Increasing the profitability of logistics operations
Ease of use	Convenient interface and accessibility for users of different levels	Increasing staff efficiency, reducing training
Data security	Protecting information from unauthorized access and loss	Ensuring confidentiality and reliability of the logistics system

increase the speed of decision-making and reduce the risk of errors. The flexibility and adaptability of the methods allow to respond to changes in delivery conditions and cargo volumes. In general, the implementation of such approaches contributes to increasing the economic efficiency and reliability of the logistics processes of the enterprise. Digital technologies allow to increase the potential of logistics enterprises, in particular in the context of safety, minimizing the negative impact on the environment, and implementing modern technologies of Industry 4.0 [35].

To ensure cost-effective logistics transportation of equipment, it is necessary to optimize the organizational structure and operational processes using information technologies for data processing, improve personnel skills, and implement logistics process automation systems [36].

A comprehensive approach to developing a new innovative data processing method for cost-effective logistics transportation of equipment is shown in Figure 1.

Expected results from the implementation of the proposed data processing method for cost-effective logistics transportation of equipment:

- reduction of logistics costs by 15–25% due to optimization of routes and resources;
- reduction of equipment delivery time and increase in the accuracy of order fulfillment;
- increase in transportation reliability due to risk forecasting and scenario modeling;
- automation and adaptability of processes that ensure the stability of the logistics system to changes in market and external conditions.

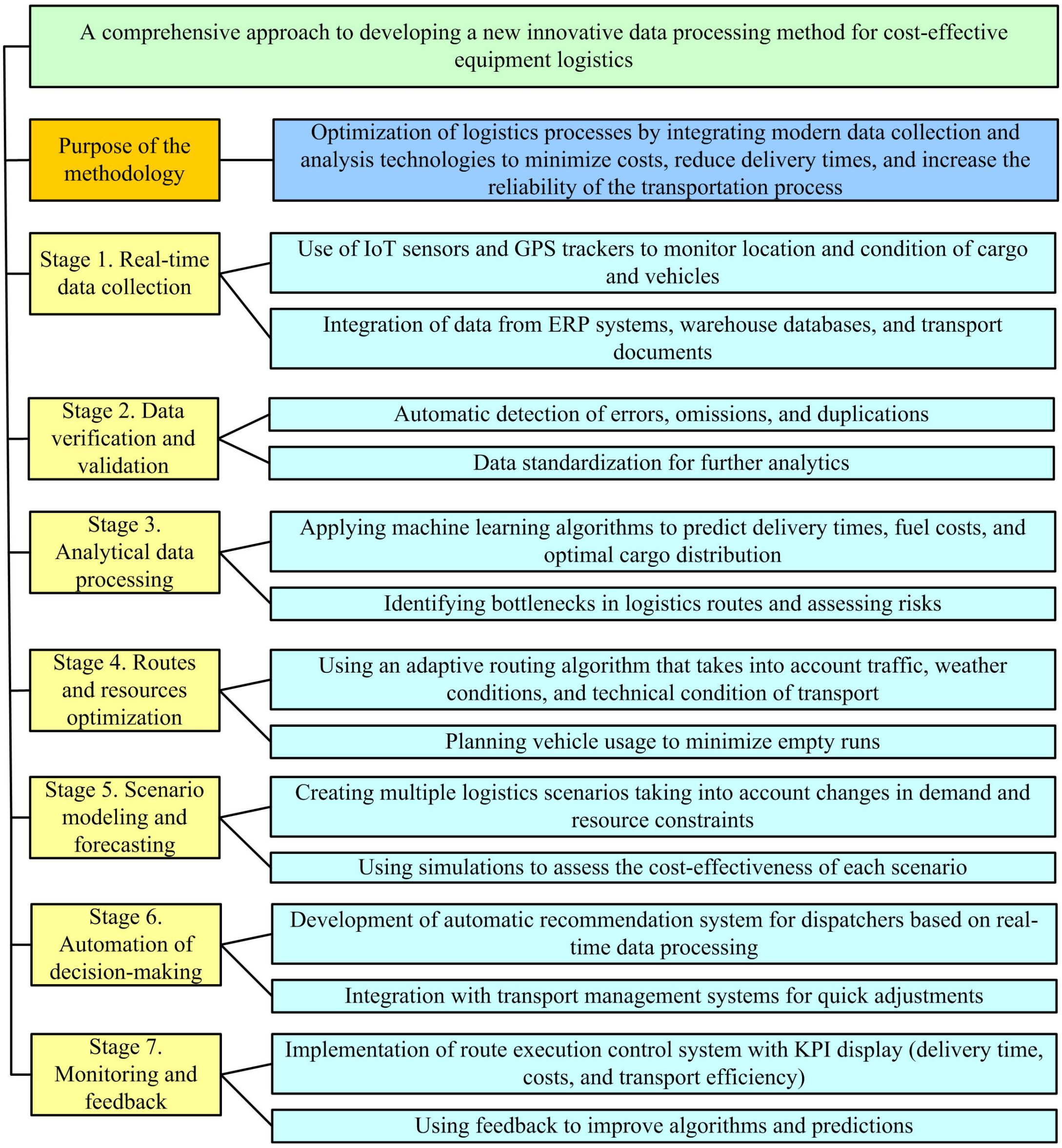

Figure 1: The comprehensive approach to developing innovative data processing method for cost-effective logistics transportation of equipment.

4. Results and discussions

This section considers mathematical models of data processing for solving the logistical problem of transporting spare parts of equipment. Let's specify the research problem.

It should be noted that the object of the study is the process of technical maintenance and repair of aviation equipment. Let's assume that these processes take place in the corresponding hubs, the structure and location of which within a given country or region are already known. The corresponding infrastructure could be built based on the use of approaches described in publications [28, 29].

In general, we propose that the generalized indicator of the effectiveness of the considered problem takes into account 4 main factors:

- delivery cost,
- delivery duration,
- risk of non-delivery,
- risks associated with failure to perform the functions assigned to aviation equipment during maintenance and repair.

The use of such an efficiency indicator refers this problem to the case of multi-criteria optimization. The partial indicators must be normalized to one in value and participates in the convolution to the integral indicator.

In this case, the minimum value must be used as the efficiency criterion.

The partial indicators of the cost and duration of delivery depend on the distance from the departure point and the destination, as well as the selected type of transport (road, rail, sea, or air transport). The risk of non-delivery is the probability that the required spare part will not be delivered due to problems with transport, the human factor, the occurrence of unforeseen or catastrophic events, and others. The fourth partial parameter is associated with the occurrence of aviation hazardous events, for example, equipment failures and their backup units, increased risks of air navigation services, and others. We denote the partial indices as γ_1, γ_2, γ_3, and γ_4.

Normalization of partial efficiency indicators is performed according to the formula:

$$\gamma_i^{norm} = \frac{\gamma_i - \gamma_i^{min}}{\gamma_i^{max} - \gamma_i^{min}}, \tag{1}$$

where γ_i^{min} is γ_i^{max} are minimum and maximum value of i-th partial efficiency indicators γ_i.

As a result of normalization, we will get that the values of the parameters γ_i^{norm} will vary in the range from zero to one.

For each partial indicator of efficiency, a separate weighting coefficients a_i are set for the convolution. In this case, the sum of these coefficients is equal to one $\sum_{i=1}^{4} a_i = 1$.

The values of the coefficients can be selected by a priori or a posteriori analysis. In the first case, it is necessary to conduct a theoretical analysis of the influence of each of the parameters on the integral indicator. In the second case, it is necessary to collect statistical data, and based on the results of their processing, establish a mutual correlation. In our case, we can take, for example, the following values of coefficients: $a_1 = 0.35$, $a_2 = 0.35$, $a_3 = 0.05$, and $a_4 = 0.25$.

The integral efficiency indicator is determined using the formula

$$\theta = \sum_{i=1}^{4} a_i \gamma_i^{norm}. \tag{2}$$

If we have$j$ alternative transportation options, then the optimization problem can be written as the formula

$$j_{opt} = \arg\min_{j \in \mathcal{J}} \sum_{i=1}^{4} a_i \gamma_{i,j}^{norm}. \tag{3}$$

The advantage of this approach is the simplicity of implementation and the ability to adjust the priority by changing the weight coefficients. In addition, the proposed approach allows to formalize the decision-making process when providing spare parts for equipment during maintenance and repair.

Let's specify the problem and make a number of limitations. We will assume that transportation is carried out by road transport. In this case, the risks are zero. That is, the third and fourth partial parameters will be excluded from the calculations.

The initial parameters of the model are the cost of transportation, the cost of the spare part, the geographical coordinates of the starting point and the final destination of the route, and a road map.

The cost and duration of the route can be considered as correlated values. Then the efficiency indicator (2) can be transformed into the length L of the path traveled by road transport.

The problem of determining the length was reduced to approximating the route (points x_s and y_s in geographical coordinates) by an implicit function $f(x, y) = 0$. This function in the general case has the form

$$f(x, y) = \sum_{m=1}^{M} \alpha_m \Phi_m(x, y), \tag{4}$$

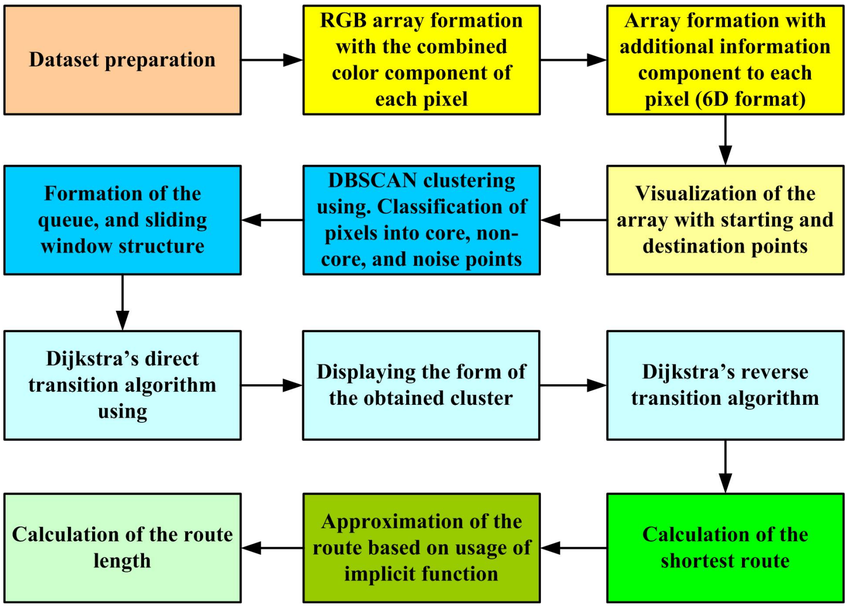

Figure 2: The algorithm of data processing.

where $\Phi_m(x, y)$ is predetermined basis function, M is a number of basis functions, and α_m are unknown coefficients need to be estimated. Polynomial functions, radial basis functions, trigonometric functions, and others can be used as basis functions.

The problem of choosing an approximating function transforms to the following form

$$\hat{f}(x, y) = \arg \min_{\|\alpha\|=1} \sum_{s=1}^{S} \left(\sum_{m=1}^{M} \alpha_m \Phi_m(x_s, y_s) \right)^2 . \tag{5}$$

After determining the approximating function, the route length can be calculated using the formula

$$L = \int_{y_0}^{y_1} \frac{\sqrt{f_x^2(x, y) + f_y^2(x, y)}}{|f_x(x, y)|} dy, \tag{6}$$

where $f_x = \frac{\partial f}{\partial x}$ and $f_y = \frac{\partial f}{\partial y}$ are partial derevatives, y_0 and y_1 are ordinate of the starting point and the final destination of the route.

The developed method of data processing is shown in Figure 2.

The developed method is based on the use of three constituent elements of artificial intelligence systems: DBSCAN clustering method, Dijkstra's algorithm, implicit function approximation.

The input dataset is the map with marked starting point and destination of the route. The image is read in RGB format, due to which the transition to a six-dimensional feature space is carried out.

The DBSCAN clustering technique was used to form possible routes. In this case, for each pixel, a decision is made as to whether it belongs to a core, non-core, or noise point. As a result, a queue of pixel points is formed, starting from the initial point of the route. According to the results of clustering, two clusters are formed, which is ensured by choosing the number of points in the neighborhood of the nuclear point and the radius of this neighborhood.

After that, for the formed queue in the main cluster, a calculation is performed according to the Dijkstra algorithm, which is used in both forward and reverse directions. As a result, a route is formed. The resulting route is approximated by an implicit function in order to calculate its length. To confirm the reliability, the calculation algorithm is repeated 10 times. Based on the results of all calculations, the shortest route is selected.

An example of the algorithm implementation is shown in Figure 3.

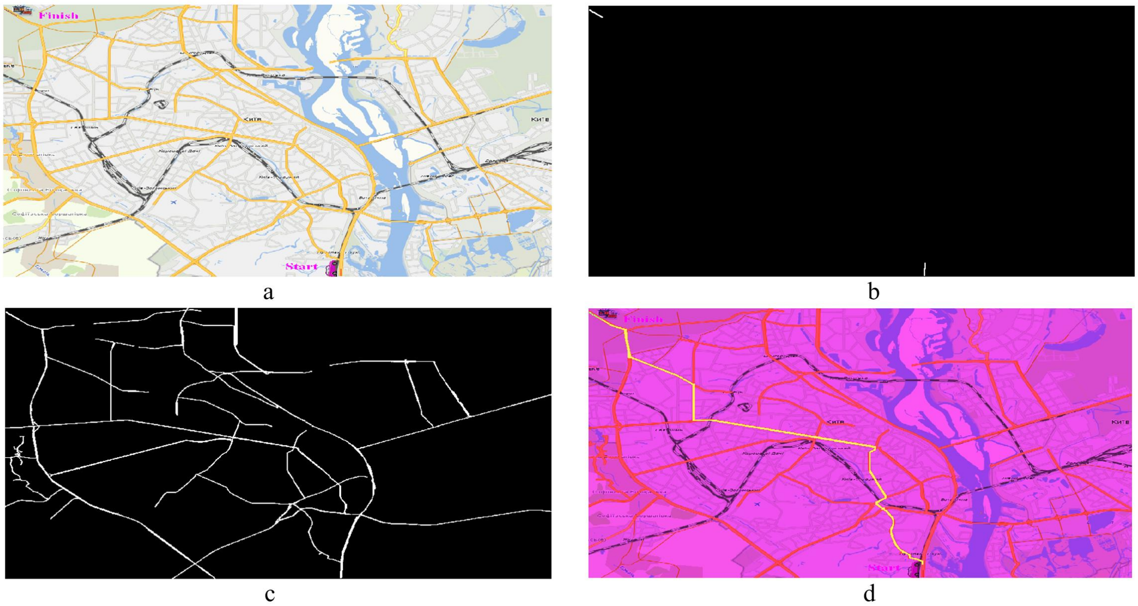

Figure 3: Example of route calculation.

Figure 3a shows the initial map with marked starting point and destination point. Figure 3b contains the image of the starting and ending points for cluster formation. Figure 3c is the result of clustering using the DBSCAN method. Figure 3d shows the optimal calculated route.

5. Conclusions

The proposed innovative data processing method for cost-effective logistics transportation of equipment allows integrating various sources of information and ensures its accuracy and timeliness. The use of analytical algorithms and machine learning contributes to route optimization, cost forecasting, and increasing the efficiency of transport resources. Adaptive scenario modeling and decision-making automation provide a quick response to changes in delivery conditions.

The paper considers mathematical methods for solving the problem of calculating the optimal route. In this case, the authors have given an integral efficiency indicator, which is calculated as the convolution of partial indicators. For a simplified model, a method for calculating the optimal route has been proposed. This method includes DBSCAN clustering algorithm, Dijkstra's algorithm, and implicit function approximation. A computer program was developed to implement the proposed method. The paper provides an example of calculations performed in this program. The results of calculations for different route maps confirmed the effectiveness of the proposed method.

The considered method allows reducing logistics costs and equipment transportation time, as well as increasing the overall reliability of processes. Systematic monitoring and feedback contribute to the continuous improvement of the logistics system. Thus, the implementation of this method ensures increased economic efficiency, productivity, and competitiveness of the enterprise.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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