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MULTI-AGENT SYSTEM AS A TOOL FOR TRANSPORT LOGISTICS PLANNING: TECHNICAL STATUS OF VEHICLES IN THE RUSSIAN FEDERATION

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Abstract. This article examines the importance of transport logistics in the Russian Federation. The authors assess the performance of transport logistics and its integral components. In the course of the research the Rosstat data and the LPI coefficient were employed in the statistical analysis. Factors that influence logistics performance were identified, including weather and road conditions, customs operations, and information support. What is more, the technical readiness and status of vehicles were examined with due respect to the logistics performance indicators that prove its efficiency. As a result, the authors suggest a method for managing transport and logistics based on a multi-agent system with predictive analytics and IoT devices that contribute to better management and forecasting in transport logistics.

Keywords: transport logistics, multi-agent system, virtual private network, technical monitoring, predictive analytics

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МУЛЬТИАГЕНТНАЯ СИСТЕМА КАК ИНСТРУМЕНТ ПЛАНИРОВАНИЯ ТРАНСПОРТНОЙ ЛОГИСТИКИ: ТЕХНИЧЕСКАЯ ГОТОВНОСТЬ ТРАНСПОРТНЫХ СРЕДСТВ В РОССИЙСКОЙ ФЕДЕРАЦИИ

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Аннотация. Данная статья посвящена исследованию значимости транспортной логистики в Российской Федерации. В ходе работы, авторами был определён уровень эффективности транспортной логистики на основании статистических данных Росстата и коэффициента LPI. Были определены ключевые факторы, влияющие на логистический процесс, такие как погодные условия, состояние дорог, работа таможни, информационная поддержка. С учетом факторов влияния на транспортную логистику, была проведена оценка технической готовности транспортных средств, и определены коэффициенты эффективности. В результате исследования, разработан подход к управлению транспортно-логистическими процессами с учётом технического состояния на основе мультиагентной системы с предиктивной аналитикой и использованием IoT устройств для улучшения прогнозирования и управления в логистике.

Ключевые слова: транспортная логистика, мультиагентная система, ВП-сеть, учет технического состояния, предиктивная аналитика

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Introduction

The ongoing globalization and rapid technological advancement make logistics and delivery management an integral component of effective business management. Adaptive route management for deliveries is a relevant and in-demand area aimed at addressing challenges related to the optimization of logistics.

Modern consumers expect not only high-quality products but also timely delivery, thus posing new challenges for companies. Increasing delivery speed and flexibility requires organizations to implement innovative technologies that can provide an automated and intuitive approach to process management (Bulatov, 2024; Chandra, 2002). In this context, adaptive route management involves the use of methods and tools that enable dynamic and effective response to changes that arise during transportation. Key factors contributing to the successful adaptation of delivery routes include changing traffic conditions, fluctuations in demand, unforeseen climate events, and human factors (Zayats, 2019; Zhou, 2023).

Materials and Methods

In this research, a comprehensive approach based on a systemic analysis of existing scientific papers and practical experiences was used to examine the choice of management methods in transport logistics.

Results and Discussion

This research examines the application of a multi-agent system in transport logistics in the Russian Federation, focusing on the use of motor vehicles. It also explores its shortcomings and operational specifics.

In the Russian Federation, transport logistics takes a leading position in the economy due to the country's vast size and the diverse locations of its major economic centres. The share of transport costs in GDP in 2025 amounts to approximately 20%. In this respect, the Russian Federation ranks among the top 30 countries, making transport logistics the most important component of the Russian economy.

The significance of transport logistics for the Russian Federation should also be described with the help of the Logistics Performance Index (LPI). This index characterizes the convenience and relative ease of delivery, both nationally and internationally. It also measures the timeframe and percentage of on-time delivery (Ilyin, 2014; Kalinina, 2024; Malysheva, 2022). According to the Logistics Performance Index, the Russian Federation ranks 75th out of 100. Russia's score on this index is 2.6. By comparison, Germany and the Netherlands each have a score of 4.1.

Such a low position is influenced by several factors: country size, weather conditions, road quality, customs operations, and information tracking during the delivery. Table 1 presents the countries' areas in descending order.

Table 1. Areas of countries in descending order.

Country	Area, km^2
Russia	17 098 242
Canada	9 984 670
USA	9 833 517
China	9 596 960
Brazil	8 515 770
Australia	7 741 220
India	3 287 263
Argentina	2 780 400
Kazakhstan	2 381 740

Customs operations in the Russian Federation rank 96th out of 100 countries. Communication and cargo tracking issues also arise in remote parts of the country. Tracking the delivery of material assets is particularly challenging.

In most cases, transport logistics involves not only road transport but also other means. Various modes of transport are used to deliver material assets in order to boost the efficiency and cost-effectiveness of logistics (Makarov, 2012; Nikitin, 2024).

One of the main bottlenecks of transport logistics is the low-quality of road infrastructure. Another major challenge in transport logistics is weather conditions, which greatly impact the complexity of delivery and quality of road surface (Egorov, 2020; Glushchenko, 2019). Table 2 and 3 provide data on the compliance of highways with regulatory requirements by region (Rosstat based).

Table 2. Compliance of roads with regulatory requirements.

Region	Share of roads that meet the standard	Density of paved roads per 1000 km^2
Top 20 Road Quality Projects		
Moscow	97.6	2521.6
Khanty-Mansi Autonomous Okrug - Yugra	88.4	11.7
Krasnodar Krai	88.4	481.0
Chelyabinsk Oblast	84.1	248.6
Republic of Ingushetia	82.8	1024.5
Belgorod Oblast	77.3	732.0
Republic of Adygea	77.1	578.8
Yamalo-Nenets Autonomous Okrug	74.9	3.7
Sevastopol	74.8	1213.5
Republic of Dagestan	74.2	477.5
Moscow region	73.9	848.8
Tyumen Oblast	72.8	93.2
Khabarovsk Krai	71.4	12.8
Chukotka Autonomous Okrug	71.3	1.3
Kemerovo Oblast	71.2	183.1
Saint Petersburg	70.7	2542.4
Republic of Bashkortostan	67.1	325.1
Republic of Tatarstan	65.2	476.0
Stavropol Krai	65.0	280.7
Perm Krai	64.5	146.9
Total for the country		
Russian Federation	54.1	65.6

Table 3. Total road length by regions.

Region	2022	2023
Central Federal Region	230 405.6	231 030.7
Northwestern Federal Region	74 316.2	74 513.3
Southern Federal Region	110 660.3	113 446.4
North Caucasian Federal Region	68 819.8	68 925.7
Volga Federal Region	254 986.2	255 527.8
Ural Federal Region	62 269.6	62 722.3
Siberian Federal Region	135 634.7	134 621.8
Far Eastern Federal Region	70 932.2	71 460.2
Total for the country		
Russian Federation	1008 024.6	1012 248.2

According to Table 1, — only 54.1% of the Russian Federation's roads are open, with a road density of 65.6 km^2 per 1.000 km^2 — it is clear that one of the main problems in transport logistics is poor-quality roads. This issue impacts the condition of logistics vehicles and, subsequently, increases the economic burden for their maintenance, provokes emergencies, hinders the on-time delivery, and damages to material assets on the way.

One of the main factors in transport logistics is the wear and tear of a logistics vehicle. Any transport vehicle has a lifespan, and in some cases, it can vary depending on road and weather conditions. It also touches upon the distribution of resources and modern approaches to minimizing costs and increasing efficiency under resource constraints (Kuznetsova, 2013; Li, 2021).

One of the key challenges in transport logistics is determining the actual lifespan of a logistics vehicle, taking into account maintenance costs versus the residual value. This requires continuous and systematic analysis of several parameters, including the vehicle condition, efficiency, and road quality.

Another challenge should also be considered: insufficient information support during delivery, resulting in delays and emergencies. Despite today's high level of information support and automation, communication and delivery process tracking issues do persist. International and long-distance deliveries particularly suffer from this imperfection.

Due to the aforementioned problems in transport logistics, the average vehicle utilization rate was 22%. Based on over 15.000 measurements, the following freight vehicle utilization pattern was recorded: 56% of vehicles were completely empty, and 44% were loaded. More than 80% of rolling stock (freight vehicles) travelling from the Siberian and Far Eastern Federal Regions was unloaded.

A possible solution to this problem involves implementing an information system capable of managing logistics vehicles by tracking them promptly, and creating up-to-date timeframes and schedules for cargo movement using GPS and GLONASS systems (Borremans et al., 2024 ; Korablev et al., 2021; Skobelev, 2011; Taniguchi, 2024).

It is also worth noting why so much attention is paid to road transport. Road transport is one of the primary modes of delivery, as it is the most mobile mode of transport, capable of delivering materials to remote parts of Russia. The imperfections of road transport lead to reduced efficiency of logistics and a slowdown in economic growth in the Russian Federation.

Transport vehicles are technologically complex machines containing over 10.000 parts. Each part or element of a logistics vehicle may have varying degrees of reliability in different conditions. Reliability is the ability of a transport vehicle to ensure its uninterrupted operation under specified conditions. Reliability is featured by such properties as longevity, trouble-free operation, and maintainability.

A transport failure is an abnormal situation when a vehicle loses its ability to perform the intended tasks. Failure most often occurs due to wear and tear on vehicle parts or excessive load. Figure 1 depicts the main failure conditions.

Maintainability is a criterion for a logistics vehicle, calculated using residual value and maintenance costs. This criterion indicates when it is most profitable and necessary to replace or maintain a transport vehicle.

The area of technical support of a logistics vehicle is a complex of interconnected technical, economic, and organizational events, which include timely organization and transfer of logistics vehicles for maintenance and ensuring their proper performance, taking into account the condition at economic value and calculations of minimum maintenance costs and safety. Such concerns as ecology, labour protection, and personnel safety are also considered.

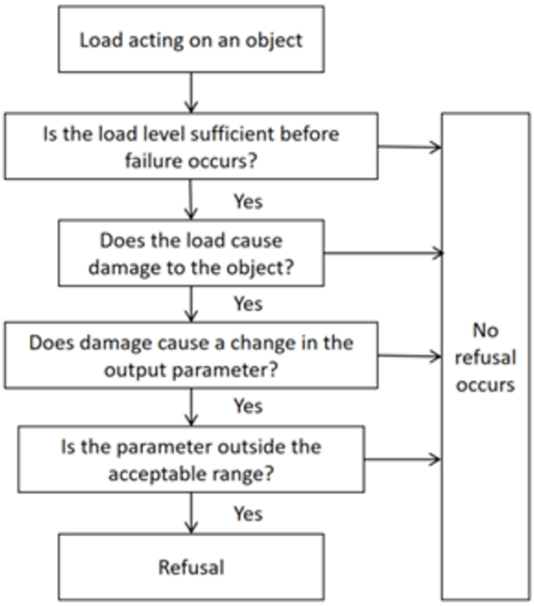

Fig. 1. Failure conditions.

There are several criteria for assessing the technical condition of transport and logistics vehicles, including timeliness and safety, maximum efficiency, operational properties, quality of the performed logistics tasks under conditions of maximum load, as well as technical condition.

Efficiency of technical support of a logistics vehicle depends on the technical support service. Depending on the type of logistics tasks, enterprises, and the location of the transportation activities, the technical support service for logistics vehicles can provide the functions of a production structure based on a specific enterprise – an independent entity that provides services to owners of various logistics vehicles.

The primary role of technical support is to ensure that a company or fleet of logistics vehicles is properly maintained in a timely manner. In other words, this area of support enables the most efficient use of serviceable logistics vehicles, taking into account the asset's cost.

From the point of view of logistics transport, reliability must be divided into several groups (Achatbi, 2020; Alibekov, 2017):

Reliability of vehicles during production and design – achieved by designing components with a reserve to withstand the loads that will be encountered during vehicle operation;

Reliability of vehicles during the operational phase – for example, limitations on the load capacity and speed.

Every year, the demands on the reliability and safety of logistics vehicles increase because the economic system demands greater efficiency and an increase in the number of deliveries. However, as the demands and number of vehicles increase, the maintenance-associated problems arise. In most cases, vehicle maintenance is untimely and poorly performed. This arises from a number of issues: lack of qualified personnel; outdated maintenance equipment; lack of a wide-scale system for diagnosing failures. These problems are logically more relevant for the remote regions.

The primary objective of assessing the technical status of logistics vehicles is to study changes in reliability criteria, taking into account most delivery route conditions, such as weather and regional road quality. The operating conditions of individual vehicle models should also be considered, as the reliability of the same components may vary across models. Another objective is to study the algorithm for economical vehicle operation and timely maintenance until the vehicle can continue to generate adequate profits.

Thus, there is a need to create a system that will take into account the technical condition of the vehicle, as well as its management with the maximum efficiency. Taking into account the abovementioned factors, it is necessary to determine which management system will most effectively manage the fleet of vehicles in terms of their technical readiness.

For a more detailed analysis, key performance indicators are provided below. These are necessary for a quantitative analysis of transport logistics performance.

Key performance indicators of the technical support of a logistics vehicle:

Technical Readiness Coefficient (TRC):

$$TRC = \frac{Number\ of\ serviceable\ vehicles}{Total\ number\ of\ vehicles\ in\ the\ fleet} * 100\%$$

Mean Time To Repair (MTTR):

$$MTTR = \frac{Total\ time\ spent\ on\ repairs}{Number\ of\ vehicle\ failures}$$

Mean Time Between Failures (MTBF):

$$MTBF = \frac{Total\ operating\ time\ of\ the\ vehicle}{Number\ of\ vehicle\ failures}$$

Percentage of Unscheduled Repairs (UOR):

$$UOR = \frac{Number\ of\ unscheduled\ repairs}{Total\ number\ of\ repairs} * 100\%$$

Maintenance costs for a vehicle per 1 km:

$$cost\ per\ kilometer = \frac{Total\ vehicle\ maintenance\ costs}{Total\ mileage\ of\ the\ vehicle\ fleet}$$

Reduction of Accident Situations (RAS) on public roads:

$$RAS = \frac{Number\ of\ road\ accidents\ up\ to - Number\ of\ accidents\ after}{Number\ of\ road\ accidents\ up\ to}$$

Key performance indicators from a logistics perspective:

Vehicle Fleet Rate (VFR):

$$VFR = \frac{Vehicle\ operation\ time\ (on\ the\ route)}{Total\ explotation\ time} * 100\%$$

On Time In Full (orders completed on time – OTIF):

$$OTIF = \frac{Number\ of\ on-time\ delieveries\ without\ incidents}{Total\ number\ of\ delieveries} * 100\%$$

Once the key performance indicators for the future system have been identified, it is necessary to consider several solutions that will shape the basis of the logistics management system.

Telematics and the IoT will enable the real-time collection, analysis, and use of data on the vehicle status and fleet management. They can be installed in various vehicle parts, such as the engine, transmission, chassis, and electrical components. Each engine type will track the necessary parameters for maintaining the vehicle's technical condition. At the same time, the use of GLONASS will enable the tracking of other important parameters, such as speed, location, and vehicle operating mode.

Another option that could form a management system is the development of digital twins. A digital twin is a virtual copy of a physical object that can reflect the condition and behaviour of a vehicle in real time (Kardashova, 2016; Kiryushin, 2019). This twin will allow for the prediction and real-time monitoring of the vehicle's technical status, as well as its failures. A digital twin includes the real object, IoT devices, and a digital model of the vehicle.

Another missing element for the vehicle control system is a predictive analytics unit. This unit is needed to analyze data coming from the IoT devices, which is difficult for humans to interpret. Data from complex powertrains (engine, transmission) will be analyzed using machine learning. This is necessary to predict the failure of any component in the vehicle and promptly dispatch the vehicle for scheduled maintenance.

One of the most promising approaches to optimizing logistics processes in this area is the use of multi-agent systems (MAS). These systems are distributed software solutions consisting of multiple interacting agents, where each performs specific functions and tasks.

Multi-agent systems have features that are particularly suitable for logistics management systems, including:

Flexibility and Adaptability. Multi-agent systems provide high flexibility and adaptability in logistics process management. Each agent can respond to changes in real time, reacting to unscheduled repairs, loss of connection to the system, route changes, or order sequencing. This allows for rapid adaptation to new conditions and minimizes negative economic impacts.

Route and resource optimization. Agents in a multi-agent system can effectively interact with each other to optimize delivery routes and distribute vehicles. Using routing algorithms and data analysis, such systems can find the most efficient routes, reducing transportation costs and delivery times. This is especially important in situations with limited resources and the need to respond quickly to various situations.

Risk reduction and increased fault tolerance. The use of multi-agent systems helps reduce the risks associated with logistics operations. Thanks to the decentralized structure, failures in the operation of a single agent do not lead to the shutdown of the entire system. This increases the resilience of logistics processes and allows for faster recovery from unforeseen situations.

The multi-agent system will be implemented using neural networks (reinforcement learning) with a virtual machine learning network structure. This approach to multi-agent systems will shift their operational methodology from reactive coordination to predictive analytics.

The implementation of neural networks will expand the functionality of agents from simple programs with conditions to adaptive control elements capable of learning and prediction. In other words, each agent in the system is equipped with its own neural network that analyzes big data and real-time data. For instance:

Cargo agent. Predicts the risk of delays on a specific route segment (by analyzing the weather, traffic jams, and the history of downtime at a specific warehouse).

Logistics Agent. Analyzes peak loads at loading centres and adjusts the arrival times of logistics vehicles to minimize downtime during loading and unloading.

Vehicle Status Agent. Predicts the likelihood of vehicle failure using predictive analytics, based not only on current IoT metrics but also on past correlations.

Conclusion

As a result, it can be concluded that a multi-agent system will improve the efficiency of deliveries. The new management system will allow for rapid adaptation to changing conditions. Further development of the management system should consider many factors related to transport, including weather and road conditions, technical and information support, as well as the technical status of the vehicle fleet. In the process of implementation, it will be also important to consider such integral parameters as the work and rest schedules, and driver safety.

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