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Advances and Emerging Trends in Evolutionary Computation for Complex Optimization under Uncertainty and Systemic Risks: Insights from the Transport and Logistics

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Abstract. The article explores innovative approaches, current trends and prospects for the application of evolutionary computing to solve complex and complex problems of the transport and logistics industry in conditions of turbulence, uncertainty and systemic risks. The need to transition from static optimization to dynamic, multi-criteria, adaptive and risk-oriented models is substantiated. The prospects for hybridization of evolutionary algorithms with artificial intelligence, machine learning, Big Data and digital twins are considered. It is shown that the further development of evolutionary computing contributes to the formation of adaptive, intelligent and sustainable logistics systems capable of quickly responding to environmental changes and systemic risks.
Keywords: *evolutionary computing; transport and logistics industry; intelligent optimization; dynamic optimization; multi-criteria optimization; uncertainty; systemic risks; adaptability; artificial intelligence; machine learning; Big Data; digital twins; sustainability of logistics systems.*

Introduction. The entire modern service sector, including the transport and logistics industry, is developing in conditions of increasing dynamism [1], multivariateness and unpredictability of the external environment [2]. Changes in transport flows, prices for fuel and energy resources, availability of infrastructure, demand [3], delivery times, geopolitical conditions, regulatory restrictions and technological parameters [4] = form fundamentally new requirements for management methods (including modeling) of logistics systems [5]. In such conditions, traditional deterministic and static optimization methods are limited, since they assume relatively stable task parameters [6], while real transport and logistics processes are characterized by continuous changes in input data, conflict of goals, incomplete information and the presence of events that are difficult to predict [7]. That is why, the search for intelligent computational approaches capable of ensuring effective decision-making not only in the presence of accurate initial data, but also under conditions of uncertainty, dynamics and systemic risks [9] is of particular relevance (in particular for the modern transport and logistics industry).

One of the promising areas in such conditions is Evolutionary Computation [10], which combines genetic algorithms, evolutionary strategies, genetic programming, differential evolution [11], evolutionary multi-criteria algorithms and other population search and optimization methods [12]. Their fundamental advantage lies in the ability to explore complex decision spaces without the need for strict analytical formalization of the objective function and to use adaptive search mechanisms in conditions of many alternatives [13].

The transport and logistics industry is a particularly illustrative object of the application of evolutionary computing [14], [15], since it simultaneously addresses the following tasks [16]: routing, resource allocation, scheduling, transport flow management, warehouse operations optimization, supply and transportation synchronization, and even multi-criteria management of costs, time, service quality, stability and risks. Additional complexity is created by the need to take into account the interdependence of individual elements of the logistics system, as a result of which a locally optimal solution can ensure the optimal functioning of the entire system [17].

Taking into account the above, the current goal of this publication is precisely to systematize innovative approaches, identify modern trends and determine the prospects for the development of evolutionary computing as a tool for solving complex and complex transport and logistics tasks in conditions of turbulence, uncertainty and systemic risks.

To achieve this goal, it is necessary to determine the specifics of the application of evolutionary computing in dynamic logistics systems; to reveal the possibilities of hybridizing evolutionary algorithms with artificial intelligence, machine learning, Big Data and digital technologies; to consider promising areas of multi-criteria, dynamic and risk-oriented optimization; to determine the conditions for increasing the adaptability and sustainability of decisions made.

Main Part. Evolutionary computing is a class of intelligent computational methods based on the principles of natural selection, inheritance, mutation, recombination and adaptation. Their essential difference from many traditional optimization methods is the ability to work with complex, nonlinear, discrete, combinatorial, multimodal and partially formalized tasks. This is especially important for the transport and logistics industry, where real management tasks are characterized by a large number of interrelated parameters, constraints and alternatives. Route construction, vehicle allocation, scheduling, inventory and warehouse resource management, supply coordination and optimization of transport flows simultaneously require taking into account cost, time, infrastructure load, reliability, service quality, environmental characteristics and the probability of various violations.

Increasing the number of such factors, the traditional search for a single optimal solution becomes increasingly complex and less adequate to the real situation. The evolutionary approach allows us to consider a multitude of potential solutions and to carry out their consistent improvement, preserving several promising alternatives and providing research into various branches of the solution space. Therefore, the innovative value of evolutionary computing in logistics lies not only in the use of individual algorithmic procedures, but primarily in the transition from a static search for a predetermined optimum to an adaptive intelligent search for a multitude of solutions capable of maintaining acceptable efficiency under changing system operating conditions.

Of particular importance is the transition from static to dynamic optimization. Transport and logistics systems operate in an environment whose parameters are constantly changing: the volumes and structure of demand vary, new orders arise, transport conditions change, delays appear, delivery schedules are disrupted, the availability of vehicles, warehouses, terminals and infrastructure facilities changes. As a result, a solution that is effective at a particular moment in time can quickly lose its rationality. Therefore, a modern evolutionary algorithm should be evaluated not only by its ability to find a high-quality solution, but also by the speed of its adaptation to changes in the external environment.

The prospects of this direction are associated with the formation of self-adaptive evolutionary mechanisms capable of changing search parameters depending on the dynamics of the situation. In a relatively stable environment, it is advisable to intensify the search in promising areas, while with a sharp change in conditions, it is necessary to increase the diversity of solutions and more actively explore new areas. In such logic, evolutionary optimization turns into a continuous process of re-optimization, focused not so much on achieving a once and for all established optimum as on maintaining the relevance and viability of the solution. This is what makes evolutionary calculations especially promising for managing logistics under turbulent conditions. Another important feature of transport and logistics tasks is their multi-criteria nature. In fact, the efficiency of a logistics system is almost always determined by a single indicator. Minimizing costs may conflict with reducing delivery time; maximizing transport loading - with the need to maintain flexibility; minimizing distance - with the requirements of route reliability; reducing costs - with environmental and service requirements. In this regard, the use of multi-criteria evolutionary algorithms allows us to move from searching for a single solution to forming a set of alternatives that reflect various compromises between cost, time, risk, service quality, environmental friendliness and sustainability.

This approach has important managerial significance. An evolutionary algorithm may not replace the decision-maker, but provide him with a set of rational scenarios from which the most acceptable option is selected, taking into account current strategic priorities. This is especially relevant under conditions of uncertainty, when it is impossible to determine in advance a universal solution that is optimal for all possible scenarios of the situation. Thus, multi-criteria evolutionary optimization expands the functionality of intelligent decision-making support systems and promotes the transition from the automatic search for a single answer to the intelligent formation of the space of management alternatives.

Uncertainty and systemic risks are another fundamental factor that determines the prospects for evolutionary computing in logistics. Incomplete information, random delays, fluctuations in demand and resource costs, technical failures, infrastructure constraints, supply chain disruptions, and other external influences can significantly change the effectiveness of the initially chosen strategy. Therefore, risk should be considered not as a secondary addition to the optimization problem, but as one of its central parameters.

In this context, the development of risk-based evolutionary algorithms that allow searching not only for the most efficient but also the most sustainable solutions becomes promising. It is important to move from assessing the probability of a single negative event to a comprehensive analysis of the sustainability of the entire logistics network. For example, a route with minimal current costs may be significantly less rational if it depends on one critically important transport node, supplier or infrastructure facility. A slightly more costly option that provides for backup routes, alternative suppliers or additional recovery capabilities may be more sustainable.

Thus, the application of evolutionary computing in the context of systemic risks contributes to a change in the criterion of rationality itself: the optimal solution is not necessarily the solution with minimal current costs, but the solution that is able to maintain acceptable efficiency under various scenarios of disruption of normal functioning. This forms the basis for the development of robust and risk-based logistics optimization.

A particularly promising direction is the hybridization of evolutionary computing with artificial intelligence and big data analysis technologies. Evolutionary algorithms have significant global search capabilities, but their application in high-dimensional tasks can be accompanied by significant computational costs. Machine learning, in turn, effectively detects patterns in large data sets and provides prediction of the future state of the system, but is always able to independently solve complex combinatorial and multi-criteria optimization tasks.

Their integration allows you to form a fundamentally new architecture of intelligent logistics, in which machine learning is used to predict demand, transport flows, infrastructure load, the probability of delays and other parameters, and evolutionary computing - to find the most effective and sustainable management solutions based on the forecast. When new data arrives, the forecast parameters can be updated, and the optimization process can adapt to the changed situation. As a result, a closed intellectual loop arises: "Big Data - forecasting - evolutionary optimization - scenario analysis - management decision - feedback."

Such hybridization fundamentally expands the role of evolutionary computing. They cease to act exclusively as an autonomous algorithmic tool and become part of a complex intelligent system capable of perceiving environmental changes, predicting their consequences, generating alternatives and adapting logistics processes.

The next promising direction is the integration of evolutionary computing with digital twins and intelligent transport systems. A digital twin allows you to reproduce the state of the transport and logistics system in a virtual environment and assess the consequences of various management influences before their actual implementation. The evolutionary algorithm in this case can use a virtual model as a search environment in which many potential solutions are consistently tested and improved.

This approach allows you to implement the principle of "first virtual optimization - then physical implementation". Its advantage is especially significant in conditions of high uncertainty and risk, since potential strategies can be pre-evaluated in various scenarios, including crisis and stress. This creates opportunities to reduce the cost of management errors, early detection of vulnerabilities in the logistics system and the formation of backup response strategies.

At the same time, modern logistics is gradually shifting the emphasis from the predominant maximization of current efficiency to ensuring a balanced combination of efficiency, stability and adaptability. Excessive optimization of individual parameters can make the system more vulnerable: minimizing reserves, concentrating supplies, reducing excess capacity and abandoning alternative routes can indeed increase efficiency in a stable environment, but at the same time increase the potential consequences of crisis disruptions.

Evolutionary computing allows us to take into account this compromise by finding solutions that combine current economic efficiency with resilience to adverse scenarios. Backup routes, alternative suppliers, inventory distribution, redundancy of transport capacity, the ability to switch between logistics channels and the speed of recovery after a disruption can be considered as elements of resilience. As a result, evolutionary optimization becomes a tool not only for increasing efficiency, but also for shaping the ability of the logistics system to maintain functionality and recover from the impact of systemic risks.

Further prospects for the development of evolutionary computing in the transport and logistics industry are associated with the formation of a new generation of intelligent optimization systems, characterized by adaptability, hybridity, multi-criteria, scenario-based, distributed and the ability to function under uncertainty. Important areas are hybrid evolutionary algorithms that combine evolutionary computer work with machine learning, neural networks and re-information learning; self-adaptive algorithms that independently change search parameters; multi-criteria optimization; real-time evolutionary optimization; robust and scenario-based search; integration with digital twins; distributed computing and intelligent decision support systems.

In the longer term, it is possible to form autonomous evolutionary-intelligent logistics systems capable of independently perceiving environmental changes, assessing their potential consequences, generating and comparing alternative solutions, taking into account systemic risks and adapting logistics processes practically in real time. At the same time, the most promising is not the complete replacement of a person by an algorithm, but the formation of a hybrid model "human - artificial intelligence - evolutionary optimization", in which the computing system provides large-scale search and scenario analysis, and the person determines strategic priorities and makes the final management decision. Thus, evolutionary computing should be considered not simply as a set of optimization algorithms, but as one of the technological components of the transition of the transport and logistics industry to an adaptive, intelligent and sustainable model of functioning. Their further evolution will be determined by the ability to integrate with other intelligent technologies and ensure not only the search for effective solutions, but also their resilience to uncertainty, turbulence, and systemic risks.

Conclusions. The analysis conducted allows us to conclude that evolutionary computations have significant potential for solving complex and complex problems of the transport and logistics industry, especially in conditions of dynamism, turbulence, uncertainty and systemic risks. Their fundamental advantage lies in the ability to perform adaptive search for solutions in complex spaces characterized by nonlinearity, multi-criteria, discreteness and changing constraints.

The modern transformation of evolutionary computations is manifested in the transition from traditional genetic and evolutionary algorithms to self-adaptive, multi-criteria, risk-oriented and hybrid intelligent technologies. Of particular importance is the integration of evolutionary computation with machine learning, Big Data, digital twins, intelligent transport systems and other artificial intelligence technologies.

For the transport and logistics industry, the transition from searching for a single statically rational solution to the formation of a multitude of adaptive and stable solutions capable of maintaining acceptable efficiency when changing external conditions is promising. In this context, it is important to take into account not only cost and time, but also risk, reliability, environmental friendliness, sustainability and the ability of the logistics system to recover.

The promising architecture of intelligent logistics can be represented as a closed loop "data → forecasting → evolutionary optimization → scenario testing → decision → feedback". Such an architecture provides a transition from reactive management to a proactive and adaptive model, in which the system not only responds to changes, but also forms alternative behavioral strategies in advance.

In general, evolutionary computing should be considered as an important element of the emerging paradigm of hybrid intelligent technologies for managing complex transport and logistics systems. Their further development is associated with increasing the speed of adaptation, integration with modern AI technologies, the use of digital twins and the development of robust multi-criteria optimization. It is this combination that can provide a qualitatively new level of sustainability, flexibility and efficiency of logistics systems in the context of continued global turbulence and increasing systemic risks.

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