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DESIGN OF AN INFORMATION AND COMPUTER SYSTEM FOR AUTOMATED CONTROL OVER TRANSPORT FLOWS AT MACHINERY AND INSTRUMENT MANUFACTURING ENTERPRISES

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This study investigates the process of managing transport flows at machine-building and instrument-building enterprises. The task addressed relates to the need for fast and effective information processing and making correct and justified logistics decisions, their automated adjustment in real time throughout the entire production life cycle.

To that end, an information and computer system (ICS) has been designed for automated management of transport flows at machine-building and instrument-building enterprises. Its operation is to determine, coordinate, and adjust technological routes for a set of transportation means (TrMs) under an automated mode and in real time when organizing production environment. It is noteworthy that the newly designed ICS covers both internal and external shop logistics levels, ensuring synchronization of territorially distributed elements of flexible production systems of machine-building and instrument-building.

Owing to the use of the ant algorithm for task distribution between TrMs and the modified A* algorithm with spatial-temporal graph expansion, the ICS capability to make operational decisions based on the "concept of compromises" has been implemented. The newly designed ICS also demonstrates high performance – preventing deadlocks in 24.9 ms and balancing the TrMs load in 500 ms.

In addition, it has been experimentally proven that the total length of technological routes has been reduced by 1.3 times, and the idle runs of TrMs by 2.5 times. It is obvious that route optimization contributes to reducing the carbon footprint, which corresponds to the Sustainable Development Goals by 2030. Also, reducing the labor intensity of work and the intellectual load on the operator has an obvious social effect

Keywords: information and computer system, automated transport flow control, metaheuristic optimization, flexible production system

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1. Introduction

Active globalization of industrial processes, especially in the fields of mechanical and instrument-making, stimulates

the dynamism of production structures. That is why the organization of modern mechanical and instrument-making production is carried out according to the principles of flexibility in the form of flexible production systems (FPSs). FPSs are

adaptive industrial systems that can quickly adjust and function effectively in a competitive environment of uncertain and dynamic consumer demand. FPS includes an extensive transport system G^{Tr} , which contains a variety of various transportation means (TrMs): from conveyors and forklifts to tow trains and automated vehicles, etc.

Current globalization of production puts new increased requirements for the flexibility, productivity, and accuracy in the functioning of a transport system G^{Tr} for FPS. After all, G^{Tr} is actually a specific technological environment of functionally interacting sets of TrMs, information related to them and other components of FPS, such as the well-known automated orientation system for production facilities (SAOOV) [1] and others. At the same time, despite the fact that TrMs increase the efficiency and flexibility of production, the task of automated control over transport flows remains relevant. In particular, this concerns determining, coordinating, and adjusting technological routes for a set of transportation means (TrMs), which determine the composition of the FPS's transport system G^{Tr} , when organizing industrial environment.

No less important is the processing of large volumes of information generated during the functioning of the FPS's transport system G^{Tr} as the globalization of production processes in mechanical and instrument-making requires constant flexible changes and transformations both in the structure of FPS as a whole and in transport flows in particular. The point is that it is extremely important to ensure the uniformity of material flows in FPS, synchronize production with market demand, minimize waste, and optimize the allocation of resources, including energy. After all, increasing the efficiency of transport flow management in FPS in mechanical and instrument-making directly affects the reduction of the carbon footprint of TrMs. And this, in turn, meets the growing requirements for environmental safety and the Sustainable Development Goals for the period up to 2030 [2].

The importance of effective transport flow management at mechanical and instrument-making enterprises is confirmed by daily practice. Thus, an analysis of existing technological processes at mechanical and instrument-making enterprises revealed that from 20% to 70% of the time is taken by auxiliary technological operations [1], including operations for transporting industrial objects (IOs). It is also known that the most frequent reason for the shutdown of both individual elements of FPS and production as a whole is not technical equipment malfunctions or shortages of materials, raw materials, or blanks, but logistical failures [3]. Situations are not uncommon when IOs accumulate or idle in neighboring workshops due to uncontrollability of TrMs or lack of coordination of their routes within FPS.

It is obvious that the management of transport flows at mechanical and instrument-making enterprises is a rather complex, multi-stage, and labor-intensive process. After all, the transport system G^{Tr} , as a component of FPS, is designed to solve the important task of organizing the production environment. In particular, the transport system G^{Tr} provides inter-shop and intra-shop movement of IOs, flows of raw materials and materials in such a way as to ensure the maintenance of a given production rhythm and a simultaneous reduction in costs. Such costs are the time of organizing the production environment, including during inter-shop and intra-shop movement of IOs, idle runs, downtime, inconsistent schedules of TrMs movement, suboptimal transport routes, etc. The main idea of the management of conveyor flows at mechanical and instrument-making enterprises is based on the well-known

"concept of compromises". In particular, the idea is that it is necessary to achieve the most effective logistical distribution of resources and costs globally in the entire FPS, and not only locally in its individual subsystems.

That is why it is necessary to offer digital tools for automated identification, tracking, and coordination of transport flows within FPS in real time. These tools should enable high speed, validity, correctness, and efficiency of logistics decision-making. After all, these decisions are critically important in managing transport flows within FPS at instrument- and machine-building enterprises at all stages of the production life cycle. Such a tool can be, for example, an appropriate information and computer system (ICS). Based on the principles of systematicity and integrity of FPS as such, the design of ICS for automated transport flow management at machine- and instrument-building enterprises should be based on a general concept of construction and a theoretical and information basis. In view of the above, it is necessary to build on the results of the research reported in [1], which relate to the development of an appropriate ICS for modeling FPS systems, in particular systems for automatic orientation of production facilities.

The purpose of the functioning of ICS for traffic flow control is to automate the process of making effective and informed decisions. These decisions concern the definition, tracking, adjustment, and coordination of technological routes for TrMs within FPS not only at the stage of technological preparation of production but also throughout its entire life cycle. The use of the ICS could significantly reduce industrial costs, in particular those arising from downtime of technological equipment, idle runs of TrMs, transport conflicts, etc. As a result, the implementation of ICS for automated traffic flow control would positively affect the speed and synchronization of material flows. This approach guarantees an increase in production performance, minimization of excess inventory and rational allocation of resources. It is important that these results are achieved in compliance with the principles of environmental safety and global sustainable development goals by 2030. Therefore, the relevance of our study is obvious.

2. Literature review and problem statement

Methods for traffic flow forecasting are comprehensively considered in [4]. It is indicated that deep learning methods have the best overall effect. However, research has focused on short-term and medium-term traffic flow forecasting, while research on long-term forecasting, which is typical for machine and instrument-making enterprises, is still relatively limited. Unlike short-term traffic flow forecasting, long-term forecasting usually lasts for months and faces problems such as unstable results, high complexity of data and models, as well as complex space-time dependences. Therefore, the task of automating traffic flow management at machine and instrument-making enterprises by designing and using an appropriate ICS remains unsolved.

In [5], a strategy for controlling a fleet of robots that perform intra- and inter-shop transport functions at an autonomous production facility is described. In this environment, repetitive transport operations are subject to real uncertainties, such as blocked passages between production areas, technological equipment, etc. and malfunctions of technological equipment and robots. In such cases, transport tasks are redistributed among robots. To overcome computational costs, a two-stage

methodology is given, within which the nominal problem is solved a priori using a Monte Carlo tree search algorithm for distributing transport tasks, which leads to the formation of a nominal search tree. When a failure occurs, the nominal search tree is quickly updated a posteriori taking into account the costs of solving a new problem, while simultaneously generating possible solutions. However, the authors focused their attention only on mobile robots and did not present solutions that could make it possible to take into account the transport capacities of the entire fleet of mobile robots at mechanical and instrument-making enterprises. The task of designing an ICS for managing transport flows as a whole also remained unsolved. Therefore, the problem of automating transport flow management at mechanical and instrument-making enterprises using appropriate ICS has not been solved.

In [6] it is indicated that one of the main ways to improve the processes of internal warehouse logistics of production is shuttle systems, which can be modernized using the concept of cyber-physical approaches. However, the information provided is fragmentary and cannot be used to build ICS for automated control over transport flows. Therefore, the task of automating the control of transport flows at mechanical and instrument-making enterprises using the appropriate ICS has not been solved.

In [7], mathematical modeling of mechatronic shuttles of multi-level systems of internal warehouse logistics was carried out. However, the study is limited only to warehouses and does not cover the entire physical structure of FPS, which is a complex, distributed system. The FPS is not limited only to warehouses. It contains both warehouse and production and other zones. That is why the transport system G^{Tr} in the mechanical and instrument-making FPS has intra-shop and extra-shop transport, the set of which forms a single logistics circuit. This is the reason why the task of automating transport flow management at mechanical and instrument-building enterprises, as well as the construction of the corresponding ICS, has not been solved in the cited work.

In [8], main modern methods of warehouse management, their differences and advantages are analyzed. Software for an automated system of logistics processes in warehouses is presented. A special server based on NodeJS has been implemented to work with user requests. However, the development is limited to only one structural unit of the enterprise and does not cover the entire set of TrMs, such as conveyors, forklifts, tow trains, automated vehicles, mobile robots, etc., which participate in the formation of transport flows. Therefore, the task of automating transport flow management at mechanical and instrument-building enterprises, as well as the construction of the corresponding ICS, has not been fully solved.

In [9], an approach to minimizing the cost of delivering goods packed in several identical containers without violating weight and volume constraints is reported, based on the branch-and-price algorithm and inequalities of subsets of rows. However, the data in the work cannot be used without additional adaptation to solve the task of automating transport flow control at instrument and machine-building enterprises. This is due to the fact that it is focused purely on international logistics and does not take into account the specifics of flexible manufacturing enterprises. Thus, the problem of automating transport flow control at machine-building and instrument-building enterprises, as well as the construction of the corresponding ICS, remained unsolved.

In [10], the basics of the ant colony method (ACO), which simulates the behavior of ants when searching for food, are de-

scribed. Despite the unusual biological metaphor, the algorithm shows excellent results on medium-sized transport problems and can be used in the corresponding ICS for automating transport flow control at machine-building and instrument-building enterprises. Thus, the task of automating transport flow control at machine-building and instrument-building enterprises is partially solved because the structure and principles of constructing the corresponding ICS are not given.

Paper [11] examines the role and possibilities of using modern technologies, namely artificial intelligence, in transport logistics management. The study focuses on how artificial intelligence can affect the efficiency and optimization of transport resource management processes, routing, delivery quality control, and warehouse management. Various aspects of using artificial intelligence are investigated, such as machine learning, neural networks, traffic control systems, voice notification systems, vehicle fleet control systems, geolocation systems in the context of transport logistics. The potential benefits that artificial intelligence provides in transport logistics management are determined, such as increasing efficiency, reducing costs, and improving service quality, automating processes, reducing errors, increasing accuracy and speed of decision-making. The results of the study demonstrate the potential of using modern technologies, namely artificial intelligence, to improve transport logistics management. However, the task of building a corresponding ICS is not posed and solved. Thus, the problem of automating the management of transport flows at machine-building and instrument-building enterprises and the construction of the corresponding ICS has not been solved.

In work [12], the possibilities of information technologies and their contributions to improving the quality of logistics operations management were analyzed. But the peculiarities of the production processes of machine-building and instrument-building enterprises, which are oriented towards their organization as FPS and the use of unmanned and unmanned technologies, were not taken into account. That is why the problem of automating the management of transport flows at machine-building and instrument-building enterprises and the construction of the corresponding ICS has not been fully solved in the cited work.

In [13], a system of automated logistics systems for warehouse management, route planning and demand forecasting is described. It is shown that the use of this system leads to a reduction in costs, a reduction in delivery times, and an increase in the efficiency of the entire chain. However, this system is focused on application only at warehouses and does not provide for the possibility of scaling it to the entire FPS of mechanical and instrument-making as a whole. The work does not take into account the specifics of functioning of the transport system G^{Tr} within FPS for mechanical and instrument-making. This specificity lies in the fact that the transport system G^{Tr} has several interdependent levels: intra-shop and external shop, which form a single logistics circuit. That is why the work does not solve the problem of automating the management of all transport flows: intra-shop and external shop within FPS. The task related to the lack of appropriate tools, for example, ICS for automated management of this process, is also not solved.

In [14], a software architectural model "Integrated Logistics Platform (ILP 4.0)" is reported, which is designed to automate the inventory processes and control the movement of goods at "smart" warehouses. ILP 4.0 works on the basis of machine learning and computer vision methods. Augmented reality (AR) and virtual reality (VR) devices are integrated into its structure. However, the functional capabilities of ILP 4.0

are aimed only at automating individual logistics operations at "smart" warehouses and do not provide for the management of all types of transport flows in general within FPS of mechanical and instrument-making. That is why the problem of effective processing of large arrays of heterogeneous information related to the functioning of the transport system G^{Tr} within FPS remains unresolved. The work lacks mechanisms for making correct and justified logistics decisions under an automated mode within FPS for mechanical and instrument-making. In particular, this concerns ensuring high-speed data processing in real time when forming and adjusting technological routes throughout the entire logistics circuit of the FPS system.

In [15], a prototype application based on the Digital Twin as a service provider for the implementation of Knowledge 4.0 is reported, so that operators can work with a highly dynamic factory floor and have "virtual control" over the physical system. The application was deployed on a real factory floor, and the test results show its potential benefits for industrial indicators in terms of productivity (cycle time and setup) and process quality standards (level of production waste).

However, issues related to the automated formation and adjustment of intra-shop and extra-shop technological routes in the general logistics circuit of FPS remained unresolved. These processes should be carried out under an automated mode with high speed in real time. After all, it is necessary to ensure the uniformity of material flows and synchronization of production. In addition, this will make it possible to minimize stocks and optimize the distribution of resources, including energy, in view of the growing requirements for environmental safety and the Sustainable Development Goals by 2030.

The reason is the complexity of a real machine-building enterprise. The fundamental impossibility of building a complete information model is the reason for designing, in this work, actually only a fragment of a digital twin. All this allows us to assert that it is advisable to conduct a study aimed at designing ICS for automated control over transport flows at machine- and instrument-building enterprises.

Thus, despite significant achievements reported in the literature [4–15], a solution has not yet been found that would solve the task of automation of transport flow control at machine-building and instrument-building enterprises. The essence of this problem is the need for fast and effective information processing and making correct and justified logistical decisions. In addition, it is important to ensure their adjustment in real time throughout the entire production life cycle and to design the appropriate effective tools, for example ICS for automated transport flow control. All this allows us to state that it is advisable to conduct research aimed at designing an information and computer system (ICS) for automated transport flow control at machine-building and instrument-building enterprises.

3. The aim and objectives of the study

The purpose of our study is to automate the process of making effective and justified decisions when forming, coordinating, and adjusting transport flows at machine-building and instrument-making enterprises.

This will make it possible:

1) to increase the speed and efficiency of processing information about the sets of TrMs within FPS transport system G^{Tr} , transport routes, and their functional relationships;

2) to make correct, effective, and justified decisions when determining, tracking, adjusting, and coordinating technological routes taking into account the interdependence of intra-shop and extra-shop TrMs, which form a single logistics circuit of FPS;

3) to reduce industrial costs arising from downtime of technological equipment, idle TrMs runs, transport conflicts, etc.

4) to ensure effective, safe, and timely movement of raw materials, materials and production facilities among structural units of the enterprise to maintain a given production rhythm.

5) to increase the speed and synchronization of material flows, production productivity, minimize excess inventory, as well as rationally allocate resources in accordance with the principles of environmental safety and the global Sustainable Development Goals by 2030.

To achieve the goal, it is necessary to solve the following asks:

- to formalize the process of controlling transport flows;
- to build a structural diagram of ICS for automated control over transport flows at machine-building and instrument-building enterprises, determine the structure of its functional modules, information flows, methods and means for automated data processing;
- to conduct experimental studies on the performance of ICS for automated control over transport flows at machine-building and instrument-building enterprises.

4. The study materials and methods

The object of our research is the process of managing transport flows at machine-building and instrument-building enterprises, in particular the process of automated determination, coordination, and adjustment of technological routes of transportation means (TrMs).

The subject of research is ICS for automated control over transport flows at machine-building and instrument-building enterprises.

The research hypothesis assumes that the implementation of tasks to design ICS for automated management of transport flows at machine-building and instrument-building enterprises could increase the speed and efficiency of information processing and making informed logistical decisions when determining, tracking, adjusting, and coordinating technological routes of TrMs.

In addition, social, economic, and environmental effects will be ensured, which will involve the following:

- reduction of intellectual and time costs for the analysis of large volumes of heterogeneous information;
- reduction of the carbon footprint in accordance with the requirements for environmental safety and the Sustainable Development Goals for the period up to 2030;
- increasing the rhythm, flexibility, synchronization of production and competitiveness of the enterprise as a whole.

Research methods are based on the application of systems analysis, graph theory, probability theory and mathematical analysis, metaheuristic optimization methods, in particular ant algorithms, as well as heuristic decision-making methods. In addition, publicly available tools from database management systems (DBMS) according to ANSI/ISO SQL standards were used.

For computer simulation, an original software product developed in Python and the Network X library used for working with graphs were applied. A modern basic personal com-

puter with an Intel(R) Core (TM) i5-11400F CPU @ 2.60 GHz, 12 MB Cache, and 16.00 GB RAM was also used. Methods of graphical representation and statistical data processing were used to treat the experimental data.

5. Results of investigating an information and computer system for automated control over transport flows at machine-building and instrument-building enterprises

5.1. Formalization of the process of control over transport flows at machine-building and instrument-building enterprises

Designing ICS requires preliminary formalization of the logistics operations of the transport system G^{Tr} and the process of control over transport flows because the transport system G^{Tr} is one of the components of FPS for machine-building and instrument-building. It is known that the transport system G^{Tr} performs the function of transporting Φ_{Tr} , which is one of the many functions performed when organizing the production environment, some of which are described in [1]. The function of transporting Φ_{Tr} involves the inter-shop and intra-shop movement of material flows: raw materials, materials and industrial objects (IOs) such as parts, assembly units, component parts, and finished products. The movement of material flows must be carried out at a given speed and the required amount of IOs, raw materials, and materials to maintain a given production rhythm and synchronism of the work of TE.

The transport system G^{Tr} within the FPS for mechanical and instrument-making is a complex ecosystem that combines interacting sets of various TE and TrMs. It has several interdependent levels: intra-shop and extra-shop. These levels differ from each other in spatial restrictions, the scale of logistical operations and the rigidity of their time synchronization with the rhythm of TE work, the accuracy of IOs positioning, types of TrMs, and the degree of their integration into the production cycle. At the same time, despite their functional differences, these levels form a single logistical contour of the transport system G^{Tr} within FPS. Thus, the arrival of an external-shop TrMs from an inter-shop route initiates a chain reaction of intra-shop movements of TrMs, and vice versa – the readiness of IOs for dispatch is the schedule driver of the work of external-shop TrMs. That is why the management of transport flows within FPS is a rather complex, multi-stage, and not always obvious process. After all, there is always a set of alternative solutions from which it is necessary to find one optimal one.

The functional interaction of the set of TrMs with the set of IOs and TE makes it possible to form a set of alternatives (technological routes), which is formally represented in the form of a weighted multigraph (Fig. 1)

$$G = (V, E, W(t)), \tag{1}$$

where V – nodes of the graph, which are TE, warehouses, intersections (crossroads) of technological routes, etc.; E – arcs of the graph, which are technological routes; W – weight coefficients corresponding to the time t of passage of TrMs at each section along the technological route.

In this case, the values of weight coefficients W are updated in real time depending on the workload of technological routes.

The dynamic change in weight w of the arc (i, j) at time t is determined as follows

$$w(i, j, t) = w_0(i, j) \cdot k_{load}(i, j, t) \cdot k_{priority}(t), \tag{2}$$

where $w_0(i, j)$ is the base time of passage of the k -th TrMs $_k$, $k = \overline{1; K}$ the section of the technological route from the i -th node V_i , $i = \overline{1; I}$ to the j -th node V_j , $j = \overline{1; J}$, respectively, which is determined from expression (3); $k_{load}(i, j, t)$ is the dimensionless coefficient of loading $V_{i,j}$ of the section, which is determined from expression (4); $k_{priority}(t)$ is the coefficient determining the degree of priority of the task.

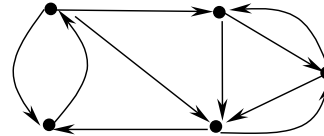


Fig. 1. Example of the form of a weighted directed multigraph

The base time $w_0(i, j)$ of passage of the k -th TrMs $_k$, $k = \overline{1; K}$ the section $V_{i,j}$ of the technological route from the i -th node V_i , $i = \overline{1; I}$ to the j -th node V_j , $j = \overline{1; J}$, respectively, is determined as follows

$$w_0(i, j) = \frac{d(i, j)}{vn}, \tag{3}$$

where $d(i, j)$ – length of the technological route section, m; vn – nominal speed of TrMs $_k$, m/s.

The load factor $k_{load}(i, j, t)$ of section $V_{i,j}$ is determined as follows

$$k_{load}(i, j, t) = 1 + \lambda \frac{K_{DTr}}{CE}, \tag{4}$$

where λ is the sensitivity coefficient, which shows how sharply the weight w of the arc (i, j) increases with an increase in the number of TrMs on section $V_{i,j}$; K_{DTr} is the total number of TrMs, pcs.; CE is the throughput of section $V_{i,j}$ along the technological route, $CE = [1; +\infty]$, pcs.

The selection of the most acceptable option is carried out from a set of alternatives according to a set of criteria. For example, at a certain point in time t there is always a set of active tasks $J(t)$, each of which has a set of identification indicators. These identification indicators include departure point, destination, cargo weight, execution time intervals, the set of available vehicles $M_{DTr}(t)$ with their current positions and carrying capacity.

These identification indicators are used for a comprehensive assessment of alternatives. On the one hand, they make it possible to predict likely positive effects, such as increasing the accuracy of IOs positioning, the speed of passing the technological route, etc. On the other hand, these indicators are used to determine costs, for example, the time to complete the technological route, the power consumed by TrMs, the consumption of fuel and energy resources necessary for the implementation of the technological route by a certain TrMs, etc. Therefore, the objective function takes the following form

$$F = \alpha \cdot T_{total} + \beta \cdot D_{total} + \gamma \cdot C_{penalty} \rightarrow \min, \tag{5}$$

where T_{total} – total delay for all tasks, determined from expression (6); D_{total} – total distance of movement of all TrMs, taking into account the usable mileage of TrMs (with cargo) and empty mileage of TrMs (movement between tasks without cargo), km; $C_{penalty}$ – penalty for conflicts between TrMs, determined from

expression (7); α, β, γ – dimensionless weight coefficients of priorities of the objective function (5), determined empirically; $\alpha > \beta$ ensures the priority of timeliness over minimization of mileage; $\alpha = 0.5; \beta = 0.3; \gamma = 0.2$ are taken.

The total delay for all tasks T_{total} is determined as follows

$$T_{total} = \sum_j \max(0, t_{end}(m) - l(m)) \cdot \pi(m), \quad (6)$$

where $t_{end}(m)$ is the actual completion time of the m -th task, where $m = 1; M$; $l(m)$ is the final deadline for the completion of the m -th task; $\pi(m)$ is the priority weight of the m -th task, which can take the following values:

$$\pi = \begin{cases} 3, & \text{for a critical task;} \\ 1, & \text{for an important task;} \\ 5, & \text{for an unimportant task,} \\ & \text{the execution of which is deferred.} \end{cases}$$

The $C_{penalty}$ penalty for conflicts between TrMs is determined as follows

$$C_{penalte} = C_{collis} + C_{dead}, \quad (7)$$

where C_{collis} is the penalty for collision of TrMs; C_{dead} is the penalty for mutual deadlocks.

The following are accepted as the constraints on task execution:

- each task can be performed only by one TrMs;
- exceeding the TrMs load capacity is not allowed;
- TrMs movement time intervals are observed, and there are no collisions.

Making the final decision on choosing the optimal technological route and the corresponding TrMs from a set of alternatives should be based on mathematical calculations. In particular, it is necessary to calculate both the probable positive effects and the associated costs given the close inte-

gration of the intra-shop and extra-shop levels of the transport system G^{Tr} within FPS. Such close integration of individual tasks necessitates the construction of an automated traffic flow control system as a single complex of software and hardware, information and telecommunications tools, and interactive functional modules according to the well-known principles of modularity and systematization [1].

5. 2. Structural diagram of the information and computer system for automated control over transport flows

It is obvious that the transport system G^{Tr} within FPS for mechanical and instrument-making is a complex system distributed in space and time. It contains a large number of structural elements, in particular TrMs, which are interconnected by heterogeneous structural, functional, informational, spatial-temporal connections. The transport system G^{Tr} functions as part of FPS, the structural diagram of which is given in [1]. In view of this, the features of the functioning of the transport system G^{Tr} and its place within FPS are appropriate, by analogy with [1], to represent by the IDEF0 model (Fig. 2). Figure2 uses the notations adopted in [1]: System of MORPE – a system of means for organizing a robotic production environment; SAOIO – a system for automatic orientation of industrial objects (IOs); DTr – transportation means; IR – industrial robot; TE – technological equipment, OD – orientation device.

In view of the above, the ICS for automated control over transport flows within FPS should be built as a cyber-physical system according to the principles of modularity, systematicity, integration, integrity, and effectiveness, a detailed description of which is given in [1]. The experience of authors of that study allows us to assert that compliance with these principles when building a newly designed ICS ensures effective integration of computing devices, algorithms, and physical objects of the transport system G^{Tr} . Such integration allows us to combine the components of the FPS transport system G^{Tr} into a holistic structure that has the properties of robustness and emergence.

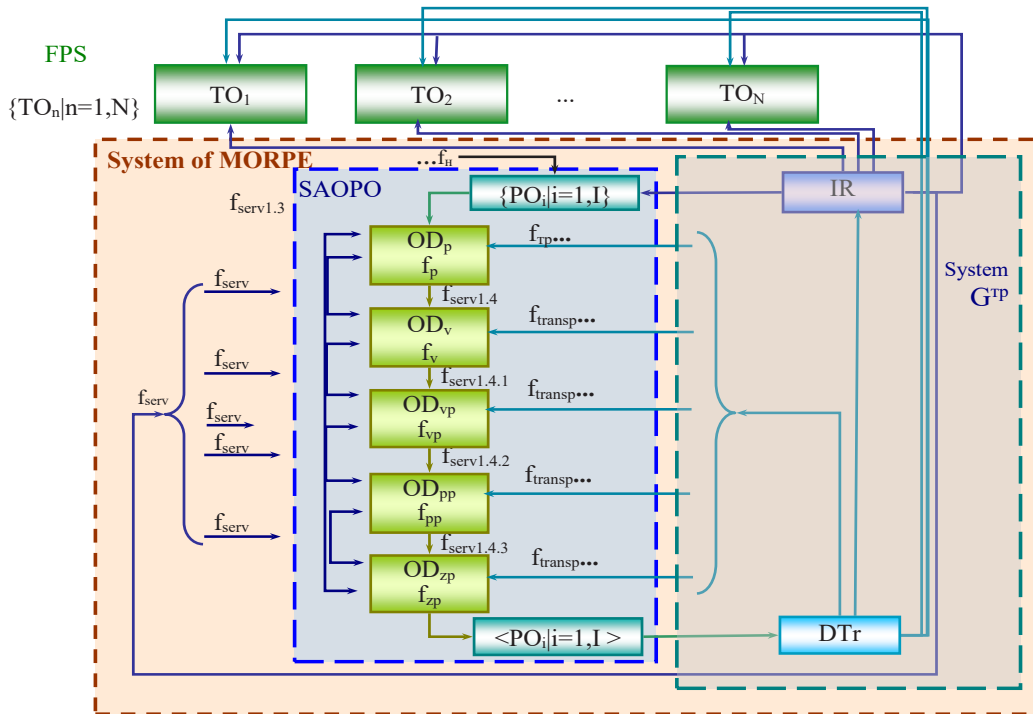


Fig. 2. IDEF0-model of the functioning of transport system G^{Tr} as part of a flexible production system [1]

In addition, the unification of physical components, scalability and changeability of software modules and algorithms are ensured if they need to be upgraded. At the same time, their functional interaction is coordinated in real time at different stages of the FPS life cycle, preventing maintenance downtime and optimizing the overall material flow.

Thus, the ICS for automated traffic flow control is an integrated complex of software and hardware solutions, information and telecommunication tools, as well as interactive functional modules, among which the processes of traffic flow control within FPS are distributed. The proposed ICS for automated traffic flow control according to the above-mentioned principles has a modular structure, which is convenient for its modernization. Also, in the ICS for automated traffic flow control, as in study [1], multi-level information protection is provided, in accordance with international requirements for the preservation of commercial secrets and the security of digital data. After all, this study is carried out as a component of a complex task for the construction of ICS for automated traffic flow control and builds on the results of the research reported in [1, 16].

Thus, the proposed structural scheme of the newly designed ICS for automated traffic flow control has a modular structure (Fig. 3). Each ICS module is focused on solving highly specialized tasks using both well-known heuristic methods and original algorithms. In particular, authentic developments are used, such as the modified A* algorithm with spatial-temporal graph expansion and the ant algorithm for distributing tasks among TrMs (Ant Colony Optimisation, ACO).

The structural composition of the modules of the newly designed ICS for automated transport flow control, as well as the corresponding tools, methods, and algorithms, are given below:

1) a database (DB), managed by a DBMS according to international ANSI/ISO SQL standards. It is used to accumulate long-term storage of data that provide solutions to specific routing problems (not shown in Fig. 3):

- technological characteristics and functionality of TrMs;
- the composition of FPSTE with which the operation of the transport system G^{TP} within FPS is coordinated;
- a set of technological routes and their characteristics (length, duration, costs for implementing the route, the base time of TrMs passage of a section of the technological route, load, priority, etc.);

2) a module of the digital twin of the transport network, which supports the current state of the graph $G(t)$, which is described by expression (1);

3) a module for planning routes according to the modified A* algorithm with spatial-temporal expansion of the graph.

The module works as follows. The modified A* algorithm with spatial-temporal graph expansion is run at each change in the state of the digital twin, i.e., the state of the graph $G(t)$ of the transport system G^{Tr} within FPS. Each vertex of the graph $G(t)$ is represented as a pair of numbers $(V, t_{arrival})$, where V is a node of graph $G(t)$, identified as a target point, t is the planned arrival time of TrMs at target point V . This allows us to predict the occupancy of nodes V and build a technological route bypassing the occupied nodes reserved in matrix $R[V, [t_{start}, t_{end}]]$. Thus, the modified A* algorithm with spatial-temporal graph expansion allows us to find the optimal route. This is a route that has not only the shortest length but also allows us to avoid collisions with other TrMs operating within FPS;

4) deadlock detection and elimination module: a condition under which the so-called traffic flow paralysis may occur, when several vehicles are waiting for each other, and none can move.

Deadlock prevention is ensured in two ways: deadlock prevention and deadlock elimination.

Deadlock prevention is carried out during route planning. For each TrMs $_i$, $i = \overline{1; I}$ nodes V_i , $i = \overline{1; I}$, as well as sections E_{ij} are reserved, where $i = \overline{1; I}$ is the serial number of the technological route, $j = \overline{1; J}$ is the serial number of the section of this route that TrMs $_i$ will pass in a certain time t . In this case, the start time of the route is conditionally denoted by t_{start} , and the end by t_{end} . This is represented in the form of the so-called reservation matrix $R[V, [t_{start}, t_{end}]]$. The modified A* algorithm with spatial-temporal expansion of the graph takes this into account and does not build a route through already reserved nodes and sections.

Deadlock elimination is carried out during constant updating of graph $G_W(t)$ (Fig. 4), in which the arc (m_i, m_j) means that TrMs m_i is waiting for the release of the node/target point V_i , $i = \overline{1; I}$, occupied by another TrMs m_j . The presence of a WG cycle on graph $G_W(t)$ (Fig. 4) indicates a deadlock. In the event of a deadlock, the TrMs with the lowest priority $\pi(m)$ of task m automatically receives a command from the automated traffic flow control ICS to retreat to the nearest free waiting space. After that, the routes are automatically reconfigured in real time;

5) the load balancing module is used to distribute tasks between a set of TrMs according to the developed ant algorithm for distributing tasks among TrMs "Ant Colony Optimization distribution of tasks between vehicles" (ACO_DTBV). The essence of the algorithm is that each "ant", which is understood as the i -th TrMs, passes a certain technological route. In this case, it is controlled by two signals: the "pheromone trail" $\tau_{[i][v]}$ (experience of previous decisions) and the "heuristic" $\eta_{[i][v]}$ (distance from TrMs to the point v of task dispatch). The selection of a specific i -th TrMs that will implement the task is carried out according to expression (8)

$$P_{[i][v]} = \frac{\tau_{[i][v]}^{q_1} \cdot \eta_{[i][v]}^{q_2}}{\sum_k (\tau_{[i][k]}^{q_1} \cdot \eta_{[i][k]}^{q_2})}, \quad (8)$$

where $\tau_{[i][v]}$ – pheromone trail (experience of previous solutions); $\eta_{[i][v]}$ – heuristics (distance from TrMs $_i$ to point v of task dispatch); q_1, q_2 – parameters of the balance between "memory" and "greed", respectively, $q_1 = 1.0, q_2 = 2.0$.

"Pheromone trail" after each iteration evaporates at a certain speed, which is given by coefficient ρ , and is replenished in proportion to the quality of the solution. For longer storage of information about previous technological routes in the proposed ICS AKTP, it is assumed that $\rho = 0.1$. The algorithm execution time limit is 500 ms, which corresponds to real-time mode. If the optimal solution is not found, the so-called "greedy" heuristics are used. Thus, the algorithm is guaranteed to return a response under a real-time mode;

6) adapter for integration with the enterprise's MES via RESTAPI;

7) operator dispatching interface for displaying the current status of the FPS transport system G^{Tr} and manual control in the case of algorithm failures.

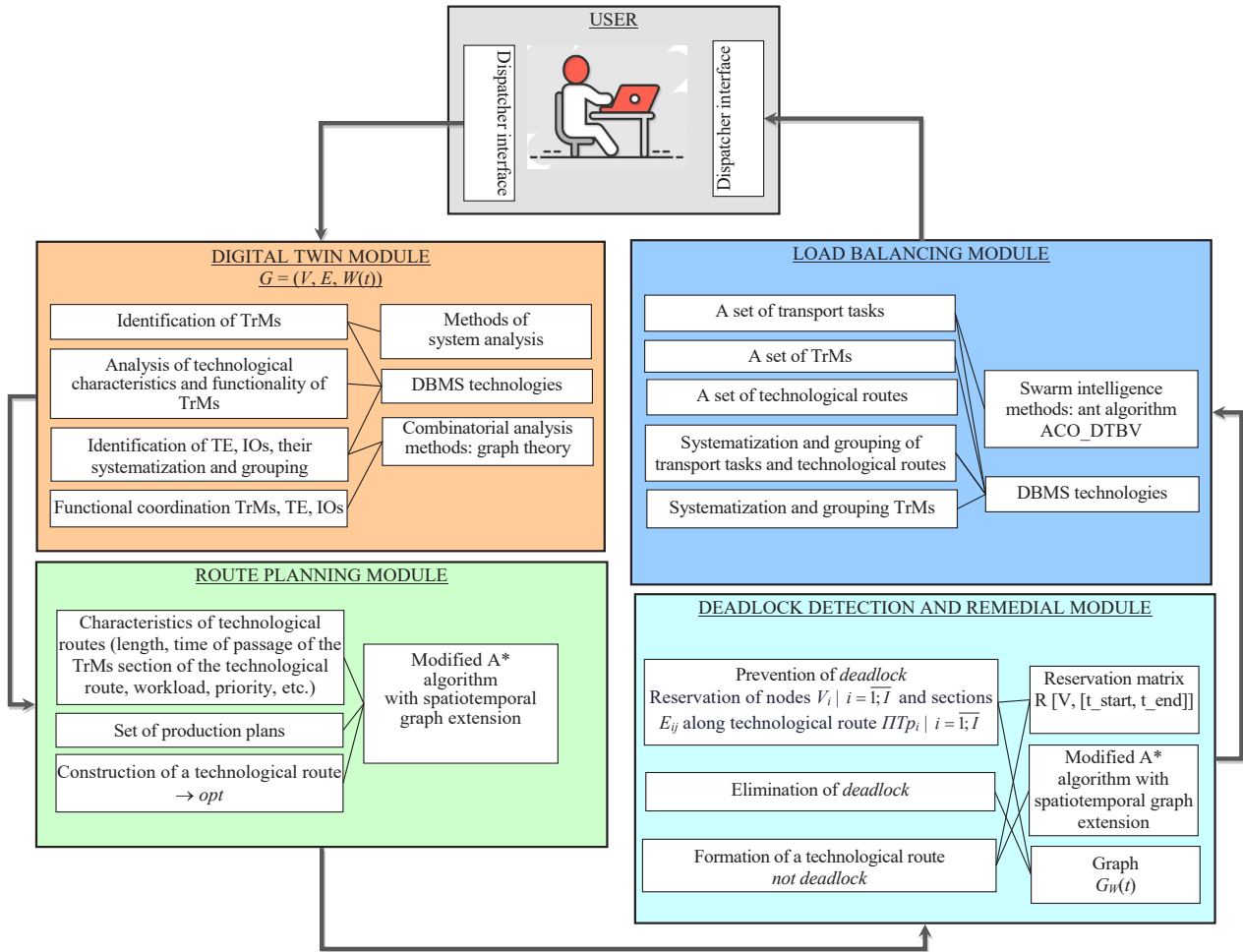


Fig. 3. Structure of the newly designed information and computer system for automated traffic flow management

5. 3. Experimental studies on the performance of the information and computer system for automated control over transport flows

Our results are given in Table 1. This abstract FPS is territorially distributed among five production shops with conditional names P1, P2, P3, P4, and P5. The structure of the FPS also includes three warehouse zones (S1, S2, S3) and a shipment zone, which is conditionally named B1. The transport network of this FPS is visualized as a graph with 38 nodes and 164 arcs (Fig. 4).

It is randomly assumed that the transport system G^{Tr} of this abstract FPS includes eight automatically guided vehicles (AGVs) with a load capacity of 500 kg and four forklifts of 2000 kg each.

Three series of experiments were conducted with different loads: 200, 350, and 500 transport tasks per shift lasting 8 hours. Each task was randomly generated according to the following parameters:

- nodes of departure and destination: evenly from all nodes of the graph;
- cargo mass: from 50 to 600 kg according to the normal law of distribution of random variables;
- task priority: 20% critical, 60% normal, 20% deferred tasks;
- execution time window: 5–20 min depending on the priority of the task.

Each series of experiments was conducted for three control modes, which were given the conditional names "MANUAL", "STATIC", and "DYNAMIC":

- "MANUAL": a manual mode, under which the determination of the technological route and the necessary set of TrMs for its implementation is carried out by the dispatcher;
- "STATIC": a mode under which route planning was carried out on an unchanging graph without updating the weights w of its arcs, in other words, without taking into account the workload of technological routes;
- "DYNAMIC": determination of technological routes by the newly designed ICS for automated transport flow control using the modified A* algorithm with spatiotemporal graph expansion and the ACO_DTBV ant algorithm.

As a result, the newly designed ICS for automated transport flow control determined transport routes for the test set of TrM sat higher speed and efficiency. A comparison of our results from transport route planning and transport flow control for each mode by a set of efficiency indicators is given in Table 1.

Under the "MANUAL" mode (Table 1), the task was assigned to the first free TrMs in a heuristic way ("greedy" assignment). In this case, the decision-making time by the dispatcher was 30–180 s or 0.5–3 min, active conflict prevention did not occur, so the probability of a conflict was 7%, and deadlock was 5.3%.

Under the "STATIC" mode, when failures occurred, it was necessary to perform a complete recalculation of routes, so the decision-making time was from 1.3 to 5 min. The probability of conflicts compared to the "MANUAL" mode decreased by 2.3 times and amounted to 3%, and deadlock decreased by 10 times to 0.5%.

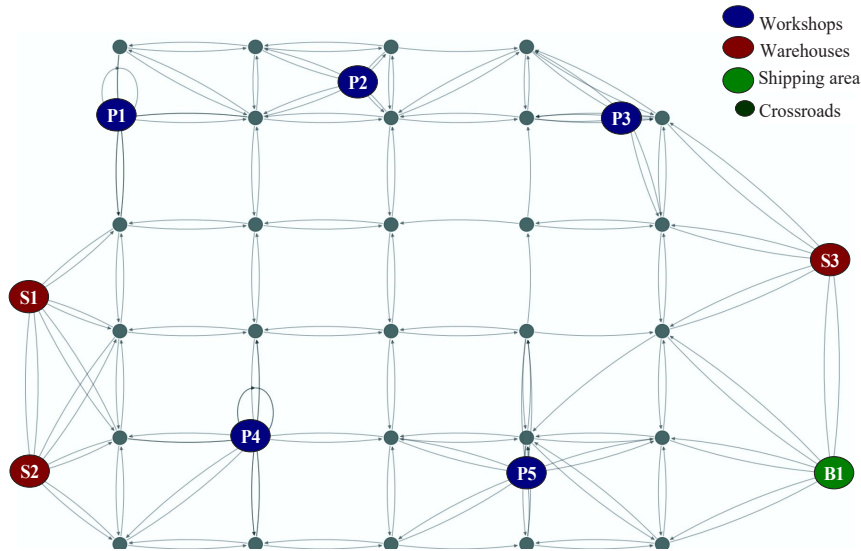


Fig. 4. Screenshot of one of the variants of the generated transport network graph of an abstract manufacturing machine-building enterprise

Table 1
Comparative results of transport route planning and traffic flow management for different operating modes

Performance indicator	Control mode		
	MANUAL	STATIC	DYNAMIC
Route planning time, min	0.5–3	1.3–5	17×10^{-3}
Route replanning time, min	0.5–3	1.3–5	7×10^{-3}
Number of conflicts per shift	25	9	1.7
Probability of conflicts, %	7	3	0.5
Mutual deadlocks per shift, %	5.3	0.5	0
TrMs load factor, %	85.5	95.5	96.7
Total TrMs mileage, km/shift	129.0	91.7	95.1
Empty TrMs mileage, %	31.4	21.8	12.6

The most effective control of traffic flows occurred under the "DYNAMIC" mode. Thus, the decision-making was carried out in real time with a speed of 24.9 ms or 7×10^{-3} min, which is 185 times faster compared to the "STATIC" mode. At the same time, the probability of conflicts has significantly decreased (by 6 times), and deadlocks have completely disappeared. Also, the empty mileage of TrMs has decreased by 1.7 times and 2.5 times compared to the "STATIC" and "MANUAL" modes, respectively, which indicates an increase in the efficiency of TrMs.

6. Discussion of results based on investigating the proposed information and computer system

The proposed ICS for automated control over transport flows within FPS of instrument and mechanical engineering is a new, original, and modern tool. It provides automated determination, tracking, and coordination of transport flows. All processes, including the correction of formed technological routes, occur in real time.

Unlike the solutions described in [6–8, 12–15], the proposed ICS for automated control over transport flows within

FPS for instrument and mechanical engineering covers the full logistics circuit. This allows one to take into account the work of TrMs both at the intra-shop and external-shop levels and synchronize the work of maintenance within FPS, as a territorially distributed multi-element system. At the same time, the social and economic effect of using the proposed ICS for automated control over transport flows is obvious. It is manifested in the fact that, unlike the solution described in [4, 5], the proposed ICS is focused on working with large volumes of data. These data have complex space-time dependences, which is typical for machine-building and instrument-building enterprises. The use of expressions (7), (8), as well as the ant algorithm ACO and the modified algorithm A* made it possible to implement the ability to respond quickly by ICS. The ICS is capable of preventing or eliminating deadlocks in the event of their occurrence with high speed (in 24.9 ms, which corresponds to real-time mode). This significantly increases the speed and efficiency of information processing and, as a result, ensures timely delivery of raw materials, materials and IOs to the structural units of FPS. In addition, the necessary rhythm and synchronization of equipment operation are maintained. At the same time, the intellectual load and labor intensity of the operator's work are reduced, which is an obvious social effect.

Also, an obvious manifestation of social and economic effects is the significant speed, in real time, of determining the optimal balance of TrMs loads. This is achieved through the use of the developed ant algorithm ACO (a detailed description is not given in this study). Unlike the known one in [10], it makes it possible to achieve the optimal balance of TrMs loads taking into account the technical and design features of the entire TrMs fleet of the FPS transport system G^{Tr} . At the same time, the duration of the algorithm execution is only 500 ms.

In addition, the newly designed ICS, unlike the solution described in [9], can search for optimal routes based on the so-called "compromise concept" for different cargoes and TrMs. The detailing and formalization of this process according to expressions (2) to (6) made it possible to determine the sequence of actions and develop a modified A* algorithm. Thus, the results of experimental studies (Table 1) showed that the total length of technological routes per shift was reduced by

1.3 times, and the length of idle (empty) runs by TrMs was approximately 2.5 times. This allows us to state that the efficiency of traffic flow management within FPS has increased. At the same time, under such conditions, the reduction of the carbon footprint in accordance with the requirements of environmental safety and the Sustainable Development Goals for the period up to 2030 is obvious. In this case, the manifestation of economic and environmental effects is obvious.

The developed structural diagram for the proposed ICS (Fig. 3) is aimed at implementing the sequence of actions when searching for and adjusting optimal routes. This process is based on the so-called "concept of compromises". Also, the architecture of the proposed ICS is based on the principles of modularity, systematicity, integration, integrity, efficiency, and security, which is a development of the results reported in [1, 16]. This guarantees the integrity and efficiency of the system. Owing to the use of unified software, hardware, and information tools, the ICS becomes suitable for further modernization and operational replacement of software components as needed.

Experimental studies on the operability of ICS for automated control over transport flows within FPS for mechanical and instrument-making were carried out for some abstract FPS, the transport network of which is visualized in the form of a graph (Fig. 4). Our results allowed us to verify not only the operability of the proposed ICS but also to confirm its high speed. In particular, the possibility of processing information in real time and making optimal decisions was proven (Table 1). Our results fully meet the requirements for modern production, environmental safety, and the Sustainable Development Goals by 2030.

It should be noted that the limitations of this study are the growing requirements for environmental safety and the need to find even more effective solutions for automated transport flow control in order to reduce the carbon footprint of TrMs in FPS. When applying the proposed ICS in practice, it is necessary to take into account the requirements for basic knowledge in the field of metaheuristic optimization methods. In particular, this applies to the features of the work of ant algorithms and heuristic decision-making methods. These same requirements remain relevant for further theoretical studies.

The main drawback of our study is the dependence of results on the completeness and reliability of information related to TrMs, FPS, material flows. In addition, the dependence of the speed of the proposed ICS on the computing power of computer equipment is obvious.

It is obvious that further development of this study could involve experimental testing of the newly designed ICS under various production conditions at real machine-building and instrument-making enterprises. That is likely to contribute to its improvement and enhance its applicability in various industrial settings.

7. Conclusions

1. We have formalized the process of traffic flow management. This formalized description reproduces the multi-stage process of making effective and justified decisions when determining, tracking, adjusting, and coordinating technological routes for TrMs in FPS. It forms the basis for the functioning of the automated traffic flow management ICS. The identified local tasks are the main tasks for the software modules in the designed ICS.

2. A structural diagram of ICS for automated control over transport flows within FPS at machine-building and instrument-building enterprises has been constructed. Information flows, methods and means of automated processing of large volumes of heterogeneous data have been determined. The proposed system provides a clear sequence of actions for determining and adjusting optimal routes. The construction of the ICS, as a component of FPS for machine-building and instrument-building, is based on the principles of modularity, systematicity, integration, and security. However, the fundamental difference of this ICS is its ability to quickly and adequately respond to changes in the production environment at all stages of the FPS life cycle. In addition, the use of unified software and hardware and original developments makes the ICS adaptive: it is relatively easy to modernize and makes it possible to quickly replace individual software modules in accordance with new production needs.

3. The performance of ICS for automated control over transport flows within FPS for mechanical and instrument-making has been experimentally investigated. Our results confirmed the feasibility of the proposed system and its capability to make justified and correct decisions when determining, adjusting, and coordinating technological routes for TrMs. The results of experimental research reported in this study confirm that the designed ICS is a new, original, and modern software tool. The ICS allows for automated and high-speed (24.9 ms, corresponding to real-time mode) control over transport flows in real time in accordance with current FPS development strategies.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Irina Cherepanska: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision; **Artem Sazonov:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Visualization, Project administration; **Dmytro Tereshchenko:** Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Petro Melnychuk:** Conceptualization, Methodology, Validation,

Data Curation, Funding acquisition; **Dmytro Melnychuk**: Conceptualization, Formal analysis, Resources, Writing – review & editing, Funding acquisition; **Sergii Kalchuk**: Conceptualization, Methodology, Validation, Funding acquisition; **Valery Yanovsky**: Conceptualization, Validation, Investigation, Funding acquisition; **Yurii Honcharenko**: Methodology, Validation, Investigation, Funding acquisition; **Oleh Sokolovskyi**: Methodology, Validation, Investigation, Funding acquisition; **Liudmyla Savchenko**: Conceptualization, Resources, Data Curation, Funding acquisition.

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