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MATHEMATICAL AND COMPUTER MODELING

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PRACTICAL AND THEORETICAL ASPECTS OF MATHEMATICAL MODELING OF THE OPTIMIZATION PROCESS OF MANAGING MULTIGROUP BEHAVIOR OF AGENTS IN DISTRIBUTED SYSTEMS BASED ON THE GWO ALGORITHM

This work focused on the applied aspects and features of the gray wolf pack optimizer or the GWO algorithm in the context of application in multi-agent distributed systems. In this paper presented scientific materials regarding the proposed own ideas, assumptions, and hypotheses for analyzing and further verification in the fields of computer sciences, optimization methods and solving of applied mathematical and engineering problems. **The object** of the research is the process of organizing distributed systems based on computational intelligence. **The subject** of the research is the organization of algorithmic interaction in multi-agent intelligent systems in the context of mathematical modeling of the optimization process of multi-group behavior management. **The goal** of the research is to investigate the key practical and theoretical applied aspects and specifics of the application of the gray wolf pack optimizer or the GWO algorithm and its modifications; to study the features of modeling the behavior of intelligent agents of a gray wolf pack under the guidance of computational intelligence. **The methods** used: the method of analysis and synthesis, abstraction and concretization, comparison and analogies, the method of mathematical modeling and the method of scientific and search experiment. **The results** obtained: 1) analyzed the solid theoretical materials in the field of applied application of the GWO algorithm; 2) analyzed the key tactical and strategical techniques of mathematical modeling of the behavior of intelligent agents; 3) formed general approaches to mathematical modeling of multi-group interaction of self-organized multi-agent formations; 4) considered and analyzed the problems of coordination and agents interaction in a multi-agent distributed system; 5) considered the applied application of multi-agent systems in problems of science, engineering, computer and robotic systems; 6) identified the main limitations of the application of the gray wolf pack algorithm (GWO). **Further developed** the concept of mathematical modeling of the gray wolf pack algorithm (GWO) using the example of separately selected tactical and strategic techniques for organizing a wolf pack in the form of a multi-group multi-agent distributed system. **Scientific novelty**: proposed a new way to solve already solved selected optimization problems (separate optimal spherical objects packing into limited container problems) that we have listed in the paper. The main idea of the paperwork is to increase the iterational speed and accuracy of the search algorithm process by using a heuristic swarm intelligence algorithm, known as the Gray Wolf pack Optimizer or the GWO index. We proposed the use of a special qualitative and numerical indicator to determine the efficiency of individual wolf pack agents by using evaluation parameters during the optimization process or in real time. Were defined new tactical and strategic methods of wolf packs organization in the process of self-organizing in a pack. **Practical Significance**: 1) we put forward an idea-hypothesis, for verification in subsequent works, which is based on multi-group multi-agent self-organization of a distributed system on the basis of qualitative and numerical indicators, which are planned to be calculated based on complex coordination-characteristic methods and heuristic dynamically changing data. It is proposed to verify the hypothesis about new calculated evaluation parameters of the effectiveness of wolf pack agents; 2) future research works are planned to expand the scope of application of the gray wolf pack algorithm (GWO) in combination with our other promising ideas in the field of computational intelligence for solving already known, but inefficiently solved optimization problems; 3) in the context of the process of mathematical modeling using the GWO algorithm, it is planned to pay attention to the problem of the artificiality of the principle of generation and distribution of a random variable in stochastic variables of the algorithm, the issues of which were not sufficiently covered in the works found in the references or can be modified to increase the efficiency of the algorithm in solving selected problems; 4) proposed as a new solution to use the GWO algorithm in the selected optimal spherical objects packing problems for solving them in more efficient way. **Conclusions:** this work considered the main practical and theoretical aspects and many-sided application of the optimization algorithm of the gray wolf pack optimizer (GWO). The applied application of this algorithm in various scientific and practical problems in the context of mathematical modeling of multigroups multiple-agents behavior was considered. The basic principles of the organization of a wolf pack were analyzed and separate strategies of coordination and hunting by a wolf pack were determined. The key characteristics and problems of the gray wolf pack optimizer algorithm (GWO) were defined and considered the ways to solve them in the most efficient way.

Keywords: computational intelligence; optimization methods; operations research; distributed systems; grey wolf optimizer (GWO); swarm intelligence; mathematical modeling; multi-agent systems; optimal packing.

Introduction. Swarm intelligence algorithms have been described from natural life forms, from their strategies of behavior and actions, in specific situations, such as hunting, protection and others [1]. Algorithms of this class are based on adaptive reactive behavior to system indicators, which change depending on the input information and by introducing a share of randomness (stochasticity) into the overall optimization process [2].

Experimentality and adaptability in the context of heuristic research methods are a set of techniques, logical methods and practices used when input information is incomplete or in conditions of complete or partial uncertainty [3].

In practice, many different approaches and techniques are used to adapt the classical version of the algorithm to the non-trivial problem being solved. In the context of this work, most of the attention is focused on the study of the gray wolf pack optimizer algorithm (GWO) and its modifications known as variations, the classical version of which, in combination with other algorithms and techniques in the field of swarm intelligence gave us a large species population of the algorithm, and you can find some of them in the works by the references [4–6]. In this research we are staying focused on the individual modifications of the gray wolf pack algorithm (GWO) as an algorithm of the swarm intelligence class that can be used in various aspects of the science, engineering, medicine, computer science and other fields of science and technology. The clear examples are presented in the research.

Key tactical and strategic techniques for modeling the behavior of the gray wolf pack (GWO) algorithm. The Grey Wolf pack Optimization algorithm (GWO) is an algorithm of the stochastic optimization and swarm intelligence class [7].

The stochasticity of the mathematical modeling of the grey wolf pack algorithm consists in introducing a random variable at each iteration stage to artificially generate the movement of the wolf population on the solution search plane. The main idea for the algorithm was taken from the nature of the hunting process, the social hierarchy of the wolf pack. The subject of the study was the behavior of the wolf on the hunt, the tactical and strategic methods of wolves [8]. The algorithmic model of the wolf pack agent system is an attempt to reproduce the tactical and strategic methods of wolves, as a species of animals under the control of a computer. The rapid adaptation of wolf and its adaptation to constant landscape changes is a specific feature of the wolf pack that should be used to quickly find optimal solutions. Important to note that the prey hunted by a pack of wolves in the wild nature is a multiple set of local solutions, among which the pack leader chooses one optimal one at this iteration (based on his experience and information from the pack) and directs the pack to the prey or the optimum point to get.

A pack of wolves, like other predators in nature, reduces the population of other animals. Wolves in nature most often hunt ungulates. A group of wolves does not often dare to attack a large herd, but rather begins to perform tricky maneuvers in order to divide the herd and attack those who have broken away from that formation. Wolves are predators that are able to travel many tens of kilometers in a day in search of prey, and the high mobility of the pack requires them to react quickly to changes and perfect coordination from each member of the unit. The leader of the wolf pack is responsible for overall coordination, and all responsibilities are distributed depending on the social hierarchy of the pack, where the position of the wolf is determined by its physical strength, experience, and endurance [9]. There is a clear hierarchy in the wolf pack, where the alpha wolf leads the pack on the hunt, the beta wolf, delta, and omega wolves carry out clear orders (Fig. 1). The leader provides instructions to the pack members, coordinates interaction, and gives signals when and where the hunting process will be started [10].

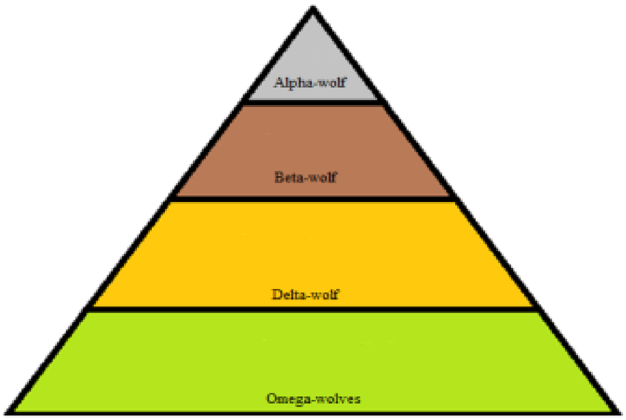

Fig 1. Social hierarchy of a wolf pack

An interesting fact about a wolf pack is that in a foreign area, the weakest and sickest wolves go ahead of the whole pack, and then all other members of the pack and the same behind the pack and the last one in the pack is know as an alpha-wolf or the pack-leader [11].

The optimization process using the wolf pack algorithm is a balance between the two strategies of "hunting and exploration of the territory". Thus, exploration of the territory is directly the process of exploring the area in order to find "a prey", which in the computer world is represented by a locally optimal solution, and whether it is better or worse than the previous one which one determined depending on the calculated value base on a fitness function we have defined. If the locally optimal solution is acceptable and the omega wolves do not find another one locally optimal solution that is better than the current local solution then the wolf pack led by alpha, beta, delta wolves begins to "hunt on the territory" and moving closer in the direction of the "victim" or the optimum point as we noted that [12].

In computer modeling various modifications of the GWO algorithm that based on the classical gray wolf pack algorithm and specific techniques make it possible to solve complex engineering, optimization, and mathematical problems [13–17].

The gray wolf pack algorithm (GWO) is a promising algorithm for implementation, and its modifications based on some of the selected swarm intelligence algorithms such as JAYA (JAYA algorithm), PSO (Particle Swarm Optimization), ALO (Ant Lion Optimizer), could be used to improve the basic indicators of the classical algorithm to bypass the known limitations of the basic implementation of the algorithm. Hybrid combined forms of these and other swarm algorithms provide better convergence speed to local or global solutions, better exploration and regularization of algorithm parameters-settings in the process of solving problems [18]. In sources [19–20] a set of selected swarm algorithms is presented for comparison of their algorithmic features and individual characteristics.

Multigroup and multiagent approaches in mathematical modeling of the gray wolf pack optimizer algorithm. A wolf pack is a group of individuals with sensory sensations united by a common goal and located in a common environment with clear hierarchical coordination that representing a group of intelligent agents or combined into a multi-agent system. You can learn more about the organization of a wolf pack in detail at [21]. Let us consider the fundamental sources [22–28], which consider the main types of agents that will be discussed in this research. In [22] the fundamental idea of creating intelligent agents capable of searching for specific information is considered. In [23] the idea-principle of non-blocking connection of a distributed agent system based on an asynchronous model of agents communication is considered. In [24–26] applied aspects of programmable agents and agents focused on information analysis are considered. In [27] an approach to organize connections between agents in the context of mathematical modeling was developed, based on the genetic programming model. The work [28] demonstrates the technique of combining or mapping (building a map of the area) by intelligent agents in the cartographic space, where intelligent agents solve the problem of recognizing and building a map of the area.

Considered the context of mathematical modeling of the optimization process of hunting by a wolf pack, in order to simplify the coordination mechanisms and hierarchical subordination of wolves in the pack the method of analogies is used. Analogy allows you to represent a complex multi-agent system in the form of intelligent computer agents or objects of the computer world. The process of creating a multi-level architecture of the agent-oriented approach can be found in the works of Martin Purvis and Y. S. Lopes, see references [29–30].

The idea of forming a multi-group multi-agent system means that interaction of two or more multi-agent groups coordinated as one structural piece, but with the distribution of tasks and responsibilities amoung few groups of wolves. There is a separate implementation of the multi-group gray wolf pack algorithm, which provides for just such multi-group behavior [31]. And in the papers of J. Li, an analysis was provided to identify patterns in the process of communication and interaction of groups of people and groups of people with AI agents for coherence quality of information exchange and to estimate the quality of coordination [32]. In the work [33] of Zhou X., which focused on flight route planning for unmanned aerial vehicles, some of the tasks listed in the paragraph above are considered and effective approaches to solve them using a multi-agent approach using the gray wolf pack optimization algorithm are proposed. To compare the obtained results and to verify the results, Zhou X. used other popular swarm intelligence algorithms, and the obtained data is presented in his work [33]. In work [34] Qunjie Liu and Hongxing Wang effectively solved the problem of planning routes for unmanned aerial vehicles using a multi-agent system based on the gray wolf pack algorithm and have confirmed that their algorithm is able to solve the task in a complex relief three-dimensional space, and their proposed algorithmic model allows to increase the efficiency by 2.34 % compared to the data obtained earlier by them.

The algorithm modification under the index Multi-strategy Fusion Improved GWO (IGWO) combines strategies in order to obtain improved convergence indicators of the algorithm on multi-extreme functions [35].

And the modification of GWO based on the K-means cluster analysis algorithm was described as an approach to increase the efficiency of finding optimal solutions based on GWO [36].

In the source [37] you can get informed with another hybrid modification algorithmical model of the on GWO base which combination with other swarm intelligence algorithms is used to increase the efficiency of finding solutions in certain specific problems.

As previously was noted in the research, wolf agents during the optimization process are oriented to the three best solutions by the general hierarchy model, which in some cases can become a significant drawback in modeling group interaction of independent wolf packs, which will block the possibility of exploring the decision plane in search of a global solution. In the work [38] Soban S. proposed to use a complex strategy that was called as "wandering-strategy" to provide dynamically adjusted parameters configuration of the wolf's exploration at the initialization stage as subsequent steps of the iteration cycle. In short, Soban S. with co-authors proposed a modification of the gray wolf pack algorithm that provides efficient and uniform exploration of the potential solution domain by the algorithm DIGWO (Distributed Improved Gray Wolf Optimizer).

The problem of multigroup interaction of agents in a complex distributed system. Controlling a group of distributed robots is an organizationally complex process, due to the dynamically changing environment, changing the position of both the robots themselves and the objects-obstacles on the map, which are not always static. More complex or group systems of constraints may be present on the solution search plane. To adapt a group of robots in special conditions with the need for real-time coordination with other robot agents, deep learning techniques are used when solving image recognition and classification problems [39]. The complexity of solving artificial intelligence tasks in the context of multi-agent interaction is that the response delay of the software component or the coordination module-component of the robot agent must be minimal. Otherwise, the relevance of the input data processed may be lost after 500 ms. from the start of some information processing has been started. Also important to note that depending on the scale of the environment map the available space for maneuver by an agent may be a small numerical value, this is why the algorithm processing time-delay so important to minimize. Worth to note that in space can be defined two-dimensional and three-dimensional problem statements for spatial orientation of multi-agent formations. In [40] reviewed and classified approaches for solving the described problems with the identification of individual limitations for the operation of multi-agent systems, where it is noted that speed, and therefore maintaining the relevance of the processed information is a key factor in the interaction, exploration, orientation and coordination of robot agents in space. In

[41] concidered the context of group search and destruction of the target and the tasks are performed in a dynamically changing environment.

Note that in conditions of complex geographical landscape, linear propagation of the radio signal means the presence of complex communication conditions between close or spread robot-agents and the need to be transmitted only important spatial information to perform the task of distributed tracking and multi-group tracking of dynamic targets [42–43]. As was shown in [44], where it is noted that during the performance of search and rescue operations by robot agents with multi-group tracking, distributed information exchange during the search, planning of general coordination and communication for the purpose of intercepting and rescuing the target – automatically means an increased probability of success of the mission being performed. Search and rescue missions are planned algorithmically so that they can be broken down into simpler subtasks, which can be partially canceled, replanned or adjusted when the dynamic parameters of the system changed and the movement route rebuilt can be performed [45]. One of the approaches for dynamic correction of the trajectory of a multi-agent robot system is a solution based on the gray wolf pack algorithm, which is described in [46] and which can be effectively combined with the intellectual component of the theory of decision-making in the context of linear multi-agent systems, as demonstrated in [47], and at the stage of final capture of the target by a special manipulator module for modified search and rescue by an agent-wolf can be done [48].

The nature of the organization of complex distributed systems requires the implementation of mechanisms for behavior of special software agents, the structure, mechanism of behavior and purpose of which vary depending on the context of the task.

We are considering [49] and [50] papers, where the main principles of organizing the work of autonomous agents, their types and examples in implementation are concentrated. In [49], Wooldridge M. J. and Jennings N. R. explained why the concept of an "agent" is important in computer science and artificial intelligence by the answering the question of how to represent an agent using a mathematical model and how to build an effective architecture of an intelligent agents distributed system that organized using effective communication principles. On the other hand, J. Refonaa et al., in [50], focused on the characteristics of intelligent agents, based on the theory of the nature and was inspired by some of the biological concepts. In addition to general information and classification of agents, in [50] presented an approach for implementing an agent communication module and some principles of simulation the behavior of robot agents. The results of the work [50] indicate for us that the obtained data can be used in modern business methodologies and in software development. In particular case, in [51] described an approach for solving certain business problems using innovative techniques based on artificial intelligence and a multi-agent approach is demonstrated. On the other hand, in [52] an automated software tool based on a multi-agent approach for solving collective business goals is presented. The social structure of a distributed system based on intelligent multi-agent formations requires an optimized computational model, which should implement a mechanism of integrity, a common mechanism of agent's movement, interaction and integration, algorithmically must be planned the distribution of available resources and communication order and so on [53]. Regarding to the communication of intelligent agents, we have separately considered the paper [54], where one from where you can be informed with an example of implementation based on large language models, which uses artificial intelligence and a multi-agent approach to provide intelligent agents with understandable commands in natural language, where a real business example of such use of the development is the implementation of the 6G network communication standard. Also in [55] researchers were able to integrate large language models and swarm intelligence algorithms as a multi-agent approach using GPT-4 program queries in combination with programming language scripts, that helped to organize the process of simulation the behavior of the autonomous process of agents interaction in intelligent system components.

Applied application of multi-agent systems based on the gray wolf pack optimization algorithm in the fields of engineering, computer and robotic systems. The GWO algorithm is an effective algorithm for solving specialized optimization problems in the fields of planning optimal routes in multi-agent robotic systems, in the problems of machine vision and pattern recognition, in the problems of deep machine learning, and modeling multi-agent systems [56]. Automated engineering sistems used swarm intelligence algorithms of inertial agents in the production of electronics, biotechnology, and various types of agents with response and without response in biomedicine [57]. The GWO algorithm is used in engineering field to optimize optimization problems solving process [58]. The classical version of GWO was applied by researchers in the work [59] for control system of unmanned aerial vehicles to adjust the parameters of PID controllers. A modification of the classical GWO algorithm developed by Abbas I. and others, in order to improve the search quality and convergence of the algorithm for tuning PID controllers in nonlinear systems and can be found by the reference [60]. The GWO algorithm is effective in solving the optimization problem for finding the balance of the generation level by power plants to ensure the desired load level on production capacities applied [61]. In spatial orientation problems, multi-agent robotic systems constantly solve the problem of optimal path planning, where the GWO algorithm has proved itself from the best side for unmanned aerial vehicles (UAVs) and mobile ground robots. The modified wolf pack algorithm MGWO (Modified Grey Wolf Optimizer) in combination with the artificial potential field method has been successfully applied in conditions of multi-extreme environments and this is confirmed by the results of the research [62].

In [63] proposed to use a modified algorithmic model of a pack of gray wolves IGWO (Improved Grey Wolf Optimization) for planning global routes for robots and unmanned aerial vehicles. In [64] the algorithmic model GWO-CSA (Grey Wolf Optimization – Sine and Cosine Algorithm) is used for effective planning of safe routes by unmanned aerial vehicles with avoidance of dangerous zones and obstacles on a two-dimensional plane.

Solving the problem of dynamic planning and resource allocation in the context of automated welding production processes is a multi-objective optimization problem, which is effectively can be solved using GWO as it displayed in [62, 65].

The ability of individual modification solutions based on the GWO algorithm to effectively explore the solution space allows its use in medicine in processing segmented images and in tasks of recognition and classification of objects in images [66].

In environmental monitoring and modeling tasks, GWO was applied in engineering, in particular cases in the optimization of processes related to pollution control and management of available resources [67].

The problem of an shortage of electricity generating capacities prompts us to hypothesize that it is advisable to optimize not only the work of large industrial consumers, but also many small households, in order to evenly distribute the available power grid resources between subscribers. We considered [68] where in the research described simulation process in an apartment building in Seattle, USA. During the specified experiment [68], the authors used the stochastic optimization algorithm of GWO with a pack size of 40 wolf agents and solved the optimization problem of minimizing the level of electricity consumption in an apartment building. Multi-criteria problems of finding the balance of household expenses are problems of the class of economic optimization of non-smooth and non-convex functions. This class of problems is often not optimally solved analytically, so it is appropriate to use metaheuristic optimization methods to find acceptable, but not exact solutions. In the context of the described problems, in [69] a potential solution to the problem is proposed, based on a modification of the classical GWO algorithm with a modification of the gray wolf pack hierarchy approach, which is aimed at improving the properties of finding solutions to minimize household costs. This method provides a better convergence speed to the solution point and has certain advantages over the wolf pack coordination property in classic version of the GWO algorithm, which is oriented towards the best solution of the alpha wolf. In [70] the author observed the phenomenon of natural disasters – earthquakes with concomitant destruction in high-rise buildings in order to study the phenomenon itself and determine the optimal parameters for setting the mass flame extinguishing components as an intelligent system based on a modification of the gray wolf pack algorithm and a genetic algorithm as combined.

An important direction of application of the GWO algorithm is to increase the efficiency of computer calculations, which is determined by a relative complex indicator that takes into account the amount of electricity consumed, the amount of heat released, the costs of associated peripherals and network services per task performed by the machine. In recent years, the cost and complexity of data-center waste recycling has been added to the list. The calculation process itself is performed by various types of processor cores, the synchronization of which is carried out under the guidance of intelligent algorithms of the operation system and research on multiprocessor and multicore systems is focused on ensuring a stable level of productivity provided that the amount of electricity consumed by the computer system is reduced. In the [71] experiments are performed with a decrease in the electrical voltage supplied to the processor and the cores of the computer, and Liu J. and co-authors investigated the problem of obtaining an optimal energy balance with an system of constraints on the time of execution of calculation operations while maintaining a stable level of reliability of the overall system. For this purpose, in [71] it is proposed to use a modified wild horse algorithm (OIWHO), and the results obtained by the authors of the work were tested and proved the rationality of using the proposed approach on large-scale optimization tasks during the distribution of sub-tasks by the processor, in comparison with other popular optimization algorithms, in particular with the genetic algorithm, the gray wolf pack, the particle swarm algorithm and others in that special case.

Abdullahi Y. U. with co-authors in [72] solved the engineering problem of drilling steel plates using the gray wolf pack optimization algorithm (Grey Wolf Optimizer) and searched for Taguchi-Paretto optimal solutions, the combination of which became rational, as noted in the work. The authors of [72] added that the experimental data for analysis were taken from the Patel and Deshpande company from their high-precision CNC machine.

In [73], scientists from the South China University of Technology proposed an algorithm for self-organization of a UAV swarm based on the gray wolf pack algorithm. In their work [73], it is noted that a UAV swarm performs tasks of varying complexity, and during a flight mission, wolf agents independently control energy resources, plan travel routes, and effective balancing and distribute tasks that performed by the central node which are reproduced in this context by intelligent UAV agents. To optimize the power consumption systems of unmanned aerial vehicles, a specialized algorithmic model was developed, which was successfully tested on specialized benchmarks using aerial vehicles [74]. Modern onboard vehicle intelligent systems require constant monitoring of system parameters for scheduled and emergency diagnostics, reliability, accuracy, and probabilistic predictive warnings to the user in dangerous situations. Such monitoring systems are required to be modular and unified for scaling production, simultaneously. This type of monitoring is performed by intelligent onboard systems by taking readings data from smart sensors. And in the reference [75] a prototype model of an intelligent system for data collection and diagnostics of vehicle operation is proposed for review. In the publication [76] presented an approach for implementing an intelligent system using state machines, as an example of a spacecraft control system, which is an ultra-complex system with ultra-high reliability standards for control components. In [77] it is noted that intelligent object identification systems are used for remote monitoring and analysis of graphic information, and the miniaturization of electronic components has made it possible to carry out such operations in real time using computational intelligence in modern spacecraft control systems.

Specifics and problems of applying the gray wolf

pack (GWO) algorithm. The gray wolf pack optimization algorithm has a list of limitations in its application and cases where the algorithm may work less efficiently compared to other algorithms of the same class of swarm intelligence. The main problems of the classical gray wolf pack algorithm include: getting stuck in local optima and not reaching the global optimum point on complex multimodal optimization functions, weak diversity of the wolf agent population, especially at the initialization stage, moderate convergence of the algorithm to the optimum points on the same complex multimodal functions [78–79]. In [80], the general case of the problem of weak diversity of the generated initial population of the gray wolf algorithm is clearly demonstrated. The iterative convergence of the algorithm to the optimum point in the least number of iterations is a key parameter of all optimization algorithms, which is optimized by various modification solutions, and in [81] a comparative analysis is carried out in the form of tables and graphs for selected modifications of the gray wolf pack algorithm on separate unimodal and multimodal test functions, where the convergence rate of different versions of the algorithm is demonstrated. Xiaobing Yu and co-authors in [82] proposed a new algorithmic solution to overcome the problem of exploration and convergence by a pack of wolf agents using a new algorithm under the index REEGWO (Reinforced exploitation and exploration GWO algorithm). In [83], Hua Qin et al. draw attention to the problem of moderate convergence speed of the gray wolf pack algorithm on complex multimodal functions, and often getting stuck in local optima, so the authors proposed a new strategy of using fuzzy methods to overcome this problem. In [84] described the case of a combination of ant colony and gray wolf pack algorithms in an algorithm under the index ACO-GWO (Ant Colony optimization – Grey Wolf Optimization) to solve the problem of improved exploration of the decision plane by wolf agents in search of a global solution. In [85], N. Singh proposed a modification to solve the problems of the classical gray wolf pack algorithm: the accuracy of the desired solution, poor ability to exit from local solutions, and moderate ability to explore the solution plane. In [86], the problem of improving the function of the gray wolf pack algorithm for finding a global solution and improving the diversity of the initial population based on a combination of the classical version of the wolf pack and hawk algorithms is considered and solved. E. Akbari and co-authors believe in [87] that the social hierarchy of wolves in the algorithmic context is the cause of some of the above problems and proposed the solution by abandoning the wolf pack hierarchy in the work that confirming this statement with benchmark results. Working on solving the described problems in the context of engineering tasks, scientists in [88] discussed individual optimization strategies in order to identify the limitations of the gray wolf pack algorithm and try to reduce their impact through new ideas and strategies to improve the research capabilities of wolf agents on the same pack population dimension. In [89], evolutionary approaches, crossover and other nature-inspired techniques are used to diversify wolf agent populations, and adaptive iterative multi-strategies are used to overcome the described problems of the gray wolf pack algorithm, which leads to improved algorithmic performance in deep learning tasks when selecting key indicators when analyzing data with an algorithm classified under the index HRO-GWO (Hybrid Rice Optimization – Grey Wolf Optimization).

In order to demonstrate the specifics of the application of the gray wolf pack (GWO) optimizer in the context of solving the engineering-automated problem of intelligent formation management, a scenario of using the GWO optimizer in the environment of energy-efficient distributed wireless multi-agent systems in the context of organizing smart cities is considered. Distributed intelligent systems in the sense of smart cities are based on multi-agent interaction of intelligent units of a holistic distributed system and the infrastructure interaction of an entire cluster of components. We add that when considering the context of smart cities, attention is focused on global optimization using the GWO optimizer. First of all, this is related to the tasks that need to be solved [90]. It is also worth adding that the classic version of the gray wolf pack (GWO) optimization algorithm, due to its algorithmic features, is not intended for solving this class of tasks, but has separate solution modifications for use in the specified context [91]. Let us consider the features of distributed intelligent systems of the “smart city” type and pay attention to why it is advisable to use the GWO gray wolf pack algorithm in this case to organize this structure. A distributed system of this type is a combination of wireless and wired networks, which are combined into one whole for a specific purpose, such as ensuring public safety, communication between the community and the authorities, ensuring community comfort, and others, where the listed features can be achieved using IoT (Internet of Things), information technologies that combine smart gadgets with video cameras, sensors and sensors of a distributed intelligent network [92]. Reference [92] clearly states that such a wireless system should be optimized in terms of energy efficiency, cluster node formation strategies, which aims to optimally place gadget communication nodes. An important parameter for placing a communication node in a “smart city” type system is the level of wireless network availability, the maximum coverage area of sensors and video cameras, which should transmit data to distributed data processing nodes continuously with minimal delay, in such a matter, an effective solution is the construction of a chaotic network map, and in more detail how to solve the issue of optimal placement of sensor formations is described in [93]. We add a separate reference to the work [94], which demonstrates the mechanism of forming an IoT network based on the GWO optimizer using specialized modification solutions based on the classical optimizer, but with different approaches and methods than was described in reference [93]. In the work [94], an analysis of the effectiveness of using this approach in industrial and commercial, user-specific application cases is carried out. In the context of this work, we drew attention to the fact that a distributed intelligent network of the “smart city” type includes hundreds, if not thousands of nodes of information transmission and reception and requires scaling depending on the size of the infrastructure and development of the city, which automatically means an increased level of load on the data transmission channel and the need for effective balancing of incoming and outgoing information messages, which is discussed in detail in work [95]. In particular, it is important to note that in work [95], an improved version of the gray wolf pack optimizer (IGWO) is demonstrated, which is designed specifically for effective solution of load balancing tasks on cluster forming nodes with an emphasis on the fact that this task can be solved effectively using metaheuristic approaches in "smart city" type systems. In work [96], a related topic of queuing tasks for their execution in IoT networks based on GWO is considered, but with one difference that the necessary calculations are proposed to be performed in a cloud environment to optimize the use and distribution of system resources at the cloud service level. A feature of the work in reference [96] is the newly proposed algorithm TS-GWO (Task scheduling grey wolf optimizer), which was specially developed based on the well-known problems of the "bottleneck" in the conditions of information exchange by thousands of peripheral gadgets that have to both send and receive data over a wireless channel simultaneously in asynchronous operation mode.

Scientific novelty. In the works [1–96] we can see that the swarm algorithms and listed modifications successfully used in presented mathematic, engineering problems etc.

As a result of applying the search-analytical scientific method to the works [1–96], we conducted a series of comparisons of the algorithms, approaches and applied practices of using heuristic algorithms of swarm intelligence described in the works. Based on the comparisons of the theoretical facts and evidence base described in the works [1–96] we defined specific advantages and disadvantages of using heuristic algorithm of swarm intelligence by the index GWO (Grey wolf optimizer).

We can conclude that the solutions of the problems described in the works [97–103] can be found in different way or the existing solutions can be improved by new proposed way to solve the problems.

We propose for the first time to use the gray wolf optimizer (GWO) to solve the problems [97–103] to increase the iterative speed and accuracy, and the efficiency of finding new solutions for the following optimization problems (the links provided for familiarization with the problems statements description): problem of balanced packing of different and equal radius circles [97], the problem of optimal packing of identical spheres in a cylinder of minimum height [98], the problem of optimal placement of equal radius circles in a container of minimum radius with forbidden zones [99], the problem of optimal packing of hyperspherical objects in a container of spherical shape [100], the problem of balanced optimal packing of spherical objects in a container of the smallest diameter [101], solving the problem of optimal packing of circles of different radius in a circular container of minimum radius [102], the problem of optimal placement of spherical objects in 2D and 3D spaces in selected range of allowed minimum and maximum distances between spherical objects [103].

It should be noted that the listed optimization problems are important to solve effectively, as they are basic problems to be solved in the field of aerospace construction, radiation diagnostics medicine, applied robotics, and military industries [104–106].

Conclusions. In this paper observed the theoretical aspects and multi-sided specific of the application of the optimization algorithm for a pack of gray wolves (GWO). By reviewing the applied application of this algorithm in various scientific and practical problems, we have come to the conclusion that from the point of view of mathematical modeling of multigroup and multiagent behavior, it would be appropriate to use this algorithm to solve specific problems that have a complex analytical solution or do not have an analytical solution to the problem at all, and must be solved by heuristic approaches.

In the paper analyzed the basic principles of organizing a wolf pack in the context of the algorithmic nature of mathematical and computer modeling. Separate strategies for coordination and hunting by a wolf pack were identified, with the aim of further development and introduction of algorithmic changes into the modeling process of the optimization-behavioral algorithm of wolves.

The work provided a general overview of the areas of application of the wolf pack algorithm, which has found application in medicine, as an element of machine learning, as a route planning algorithm in robotic systems, in engineering and production as an algorithmic part of calculating the necessary parameters in equipment configurations. Computer systems that successfully combined the versatility and efficiency of the gray wolf pack algorithm make it a valuable component in modeling tasks.

During the analysis and synthesis of the information we processed, key characteristics and problems of the gray wolf pack algorithm (GWO) were identified parameters, which significantly affect the speed of adaptation of intelligent units of distributed interaction in multi-agent systems. Such characteristics of the algorithm are: the speed of obtaining an acceptable local solution, the simplicity of calculations of one cyclic pass of the algorithm. The identified problems of the stochastic optimization algorithm class of gray wolf pack (GWO) are also its main advantages, including its fast convergence to a local solution and moderate convergence speed to a global solution or getting stuck at local points on multi-extreme functions.

Also we have clarified that in case of the lack of computing machine or a cluster of machines general power (basically, the power of computing machines can be measured in Hz per unit, but also should be checked several another even more import than amount of Hz parameters such as amount of cores, size of processing unit operation memery and few more) that we have organized for solving the problem, the GWO algorithm successfully performing the calculations in such a limited hardware environment, because of the iterations simplicity for the GWO optimizer steps.

In separate paragraphe we proposed known scientific problems to solve in different way using GWO algorithm to increase the iterative speed and accuracy, and the efficiency of finding new solutions for the listed optimization problems.

References

1. Nguyen L. V. Swarm Intelligence-Based Multi-Robotics: A Comprehensive Review. *AppliedMath*. 2024. Vol. 4, no. 4. P. 1192–1210. DOI: 10.3390/appliedmath4040064 (дата звернення: 05.06.2025).
2. Xu M., Cao L., Lu D., Hu Z., Yue Y. Application of swarm intelligence optimization algorithms in image processing: a comprehensive review of analysis, synthesis, and optimization. *Biomimetics*. 2023. Vol. 8, no. 2. Article 235. DOI: 10.3390/biomimetics8020235 (дата звернення: 05.06.2025).

3. Lui H.-P., Phoa F. K. H., Chen-Burger Y.-H., Lin S.-P. An efficient swarm intelligence approach to the Liu optimization on high-dimensional solutions with cross-dimensional constraints, with applications in supply chain management. *Frontiers in computational neuroscience*. 2024. Vol. 18. DOI: 10.3389/fncom.2024.1283974 (дата звернення: 05.06.2025).
4. Nasir M., Sadollah A., Mirjalili S., Mansouri S. A., Safaraliev M., Jordehi A. R. A comprehensive review on applications of grey wolf optimizer in energy systems. *Archives of computational methods in engineering*. 2024. Vol. 32. P. 2279–2319. DOI: 10.1007/s11831-024-10214-3 (дата звернення: 05.06.2025).
5. Negi G., Kumar A., Pant S., Ram M. GWO: a review and applications. *International journal of system assurance engineering and management*. 2020. Vol. 4, issue 2. P. 241–256. DOI: 10.1007/s13198-020-00995-8 (дата звернення: 05.06.2025).
6. Makhadmeh S. N., Al-Betar M. A., Doush I. A., Awadallah M., Kassaymeh S., Mirjalili S., Zitar R. A. Recent advances in grey wolf optimizer, its versions and applications: review. *IEEE access*. 2023. Vol. 12. P. 22991–23028. DOI: 10.1109/access.2023.3304889 (дата звернення: 05.06.2025).
7. Deep K., Gupta S., Mirjalili S. Accelerated grey wolf optimiser for continuous optimisation problems. *International journal of swarm intelligence*. 2020. Vol. 5, no. 1. P. 22–59. DOI: 10.1504/ijsi.2020.10027788 (дата звернення: 05.06.2025).
8. Hashem M. H., Abdullah H. S., Ghathwan K. I. Grey wolf optimization algorithm: a survey. *Iraqi journal of science*. 2023. Vol. 64, no. 1. P. 5964–5984. DOI: 10.24996/ijs.2023.64.11.40 (дата звернення: 05.06.2025).
9. Zvornicanin E. Grey wolf optimization algorithm. DOI: https://www.baeldung.com/cs/grey-wolf-optimization (дата звернення: 05.06.2025).
10. Шафроненко А. Ю., Бодянський Є. В. Адаптивний підхід до нечіткої кластеризації на основі еволюційної оптимізації алгоритму сірих вовків. *Збірник наукових праць Харківського національного університету Повітряних Сил*. 2023. No. 1 (75). P. 77–81. DOI: 10.30748/zhups.2023.75.11 (дата звернення: 05.06.2025).
11. Jürgens U. M. ; Grinko M., Szameitat A., Hieber L., Fischbach R., Hunziker M. Managing wolves is managing narratives: views of wolves and nature shape people's proposals for navigating human-wolf relations. *Human ecology*. 2023. Vol. 51. P. 35–57. DOI: 10.1007/s10745-022-00366-w (дата звернення: 05.06.2025).
12. Rezaei F., Safavi H. R., Abd Elaziz M., El-Sappagh S. H. A., Al-Betar M. A., Abuhmed T. An enhanced grey wolf optimizer with a velocity-aided global search mechanism. *Mathematics*. 2022. Vol. 10, no. 3. Article 351. DOI: 10.3390/math10030351 (дата звернення: 05.06.2025).
13. Li K., Li S., Huang Z., Zhang M., Xu Z. Grey Wolf Optimization algorithm based on Cauchy-Gaussian mutation and improved search strategy. *Scientific reports*. 2022. Vol. 12, no. 1. Article 18961. DOI: 10.1038/s41598-022-23713-9 (дата звернення: 05.06.2025).
14. Silaa M. Y., Barambones O., Bencherif A., Rahmani A. A new mppt-based extended grey wolf optimizer for stand-alone PV system: A performance evaluation versus four smart MPPT techniques in diverse scenarios. *Inventions*. 2023. Vol. 8, issue 6. Article 142. DOI: 10.3390/inventions8060142 (дата звернення: 05.06.2025).
15. Ou Y., Qin F., Zhou K.-Q., Yin P.-F., Mo L.-P., Zain A. M. An improved grey wolf optimizer with multi-strategies coverage in wireless sensor networks. *Symmetry*. 2024. Vol. 16, issue 3. Article 286. DOI: 10.3390/sym16030286 (дата звернення: 05.06.2025).
16. Bhatt B., Sharma H., Arora K., Joshi G. P., Shrestha B. Levy flight-based improved grey wolf optimization: a solution for various engineering problems. *Mathematics*. 2023. Vol. 11, issue 7. Article 1745. DOI: 10.3390/math11071745 (дата звернення: 05.06.2025).
17. Sharma I., Kumar V., Sharma S. A comprehensive survey on grey wolf optimization. *Recent advances in computer science and communications*. 2020. Vol. 13. DOI: 10.2174/2666255813999201007165454 (дата звернення: 05.06.2025).
18. Shial G., Sahoo S., Panigrahi S. An improved GWO algorithm for data clustering. *Communications in computer and information science*. Cham, 2022. P. 79–90. DOI: 10.1007/978-3-031-21750-0_7 (дата звернення: 05.06.2025).
19. Vargas M., Cortes D., Ramirez-Salinas M. A., Villa-Vargas L. A., Lopez A. Random exploration and attraction of the best in swarm intelligence algorithms. *Applied sciences*. 2024. Vol. 14, issue 23. Article 11116. DOI: 10.3390/app142311116 (дата звернення: 05.06.2025).
20. Qiu Y., Yang X., Chen S. An improved gray wolf optimization algorithm solving to functional optimization and engineering design problems. *Scientific reports*. 2024. Vol. 14, no. 1. Article 14190. DOI: 10.1038/s41598-024-64526-2 (дата звернення: 05.06.2025).
21. Rudowsky I. Intelligent agents. *Communications of the association for information systems*. 2004. Vol. 14. P. 275–290. DOI: 10.17705/1cais.01414 (дата звернення: 05.06.2025).
22. Jeapes B. Neural intelligent agents. *Online and CD-Rom Review*. 1996. Vol. 20, no. 5. P. 260–262. DOI: 10.1108/eb024592 (дата звернення: 10.06.2025).
23. Sycara K., Pannu A., Zeng D. D. Distributed intelligent agents. *IEEE expert*. 1996. Vol. 11, no. 6. P. 36–46. DOI: 10.1109/64.546581 (дата звернення: 10.06.2025).
24. Wong A. Intelligent software agents. *Computer communications*. 2000. Vol. 23, no. 7. P. 695–696. DOI: 10.1016/s0140-3664(99)00186-3 (дата звернення: 10.06.2025).
25. Vasilakos A. V. Intelligent information agents. *Computer communications*. 2000. Vol. 23, no. 18. Article 1790. DOI: 10.1016/s0140-3664(00)00211-5 (дата звернення: 10.06.2025).
26. Hagras H., Callaghan V., Colley M. Intelligent embedded agents. *Information sciences*. 2005. Vol. 171, no. 4. P. 289–292. DOI: 10.1016/j.ins.2004.09.006 (дата звернення: 10.06.2025).
27. Edmonds B. Modeling socially intelligent agents. *Applied artificial intelligence*. 1998. Vol. 12, no. 7–8. P. 677–699. DOI: 10.1080/088395198117587 (дата звернення: 10.06.2025).
28. Mattern S. Mapping's intelligent agents. *Places journal*. 2017. Article 2017. DOI: 10.22269/170926 (дата звернення: 10.06.2025).
29. Nowostawski M., Bush G., Purvis M., Cranefield S. A multi-level approach and infrastructure for agent-oriented software development. *The first international joint conference*, Bologna, Italy, 15–19 July 2002. New York, New York, USA, 2002. DOI: 10.1145/544741.544763 (дата звернення: 05.06.2025).
30. Lopes Y. S., Cortés M. I., Gonçalves E. J. T., Oliveira R. JAMDER: JADE to multi-agent systems development resource. *ADCAIJ: advances in distributed computing and artificial intelligence journal*. 2018. Vol. 7, no. 3. Article 63. DOI: 10.14201/adcaij2018736398 (дата звернення: 05.06.2025).
31. AlShabi M., Ghenai C., Bettayeb M., Ahmad F. F., El Haj Assad M. Multi-group grey wolf optimizer (MG-GWO) for estimating photovoltaic solar cell model. *Journal of thermal analysis and calorimetry*. 2020. Vol. 144, issue 5. P 1655–1670. DOI: 10.1007/s10973-020-09895-2 (дата звернення: 05.06.2025).
32. Li J., Huang J., Liu J., Zheng T. Human-AI cooperation: modes and their effects on attitudes. *Telematics and informatics*. 2022. Vol. 72. Article 101862. DOI: 10.1016/j.tele.2022.101862 (дата звернення: 05.06.2025).
33. Zhou X., Shi G., Zhang J. Improved grey wolf algorithm: A method for UAV path planning. *Drones*. 2024. Vol. 8, no. 11. P. 675. DOI: 10.3390/drones8110675 (дата звернення: 05.06.2025).
34. Liu Q., Wang H. UAV 3D path planning based on improved grey wolf optimization algorithm. *Frontiers in computing and intelligent systems*. 2023. Vol. 3, no. 1. P. 113–116. DOI: 10.54097/fcis.v3i1.6344 (дата звернення: 05.06.2025).
35. Hou Y., Gao H., Wang Z., Du C. Improved grey wolf optimization algorithm and application. *Sensors*. 2022. Vol. 22, no. 10. Article 3810. DOI: 10.3390/s22103810 (дата звернення: 05.06.2025).
36. Zhang X., Lin Q., Mao W., Liu S., Dou Z., Liu G. Hybrid particle swarm and grey wolf optimizer and its application to clustering optimization. *Applied soft computing*. 2020. Article 107061. DOI: 10.1016/j.asoc.2020.107061 (дата звернення: 05.06.2025).
37. Hamdan A., Tahboush M., Adawy M., Alwada'n T., Ghwanmeh S., Moath H. Phishing detection using grey wolf and particle swarm optimizer. *International journal of electrical and computer engineering (IJECE)*. 2024. Vol. 14, no. 5. P. 5961–5969. DOI: 10.11591/ijece.v14i5.pp5961-5969 (дата звернення: 05.06.2025).
38. Soban S., Sireesha R., Pavithra G., Badonia S.Grey wolf optimizer algorithm for multi-objective optimal power flow. *Journal of intelligent systems and internet of things*. 2024. Vol. 12, no. 1. P. 20–32. DOI: 10.54216/jisiot.120102 (дата звернення: 05.06.2025).

39. Zhang L., Sun Y., Barth A., Ma O. Decentralized control of multi-robot system in cooperative object transportation using deep reinforcement learning. *IEEE access*. 2020. Vol. 8. P. 184109–184119. DOI: 10.1109/access.2020.3025287 (дата звернення: 05.06.2025).
40. Dai W., Lu H., Xiao J., Zeng Zhiwen, Zheng Zhiqiang. Multi-Robot dynamic task allocation for exploration and destruction. *Journal of intelligent & robotic systems*. 2019. Vol. 98, no. 2. P. 455–479. DOI: 10.1007/s10846-019-01081-3 (дата звернення: 05.06.2025).
41. Verma J. K., Ranga V. Multi-Robot coordination analysis, taxonomy, challenges and future scope. *Journal of intelligent & robotic systems*. 2021. Vol. 102, no. 1. DOI: 10.1007/s10846-021-01378-2 (дата звернення: 05.06.2025).
42. Sung Y., Budhiraja A. K., Williams R. K., Tokekar P. Distributed assignment with limited communication for multi-robot multi-target tracking. *Autonomous robots*. 2019. Vol. 44, no. 1. P. 57–73. DOI: 10.1007/s10514-019-09856-1 (дата звернення: 05.06.2025).
43. Otte M., Kuhlman M. J., Sofge D. Auctions for multi-robot task allocation in communication limited environments. *Autonomous robots*. 2019. Vol. 44, no. 3–4. P. 547–584. DOI: 10.1007/s10514-019-09828-5 (дата звернення: 05.06.2025).
44. Queralta J. P., Taipalmaa J., Pullinen B. C., Sarker V. K., Gia T. N., Tenhunen H. Collaborative multi-robot search and rescue: planning, coordination, perception, and active vision. *IEEE access*. 2020. Vol. 8. P. 191617–191643. DOI: 10.1109/access.2020.3030190 (дата звернення: 05.06.2025).
45. Motes J., Sandström R., Lee H., Thomas S., Amato N. M. Multi-Robot task and motion planning with subtask dependencies. *IEEE robotics and automation letters*. 2020. Vol. 5, no. 2. P. 3338–3345. DOI: 10.1109/lra.2020.2976329 (дата звернення: 05.06.2025).
46. Li J., Yang F. Task assignment strategy for multi-robot based on improved Grey Wolf Optimizer. *Journal of ambient intelligence and humanized computing*. 2020. Vol. 11, no. 12. P. 6319–6335. DOI: 10.1007/s12652-020-02224-3 (дата звернення: 05.06.2025).
47. Su Y., Wang Q., Sun C. Self-triggered consensus control for linear multi-agent systems with input saturation. *IEEE/CAA journal of automatica sinica*. 2020. Vol. 7, no. 1. P. 150–157. DOI: 10.1109/jas.2019.1911837 (дата звернення: 05.06.2025).
48. Feng Z., Hu G., Sun Y., Soon J. An overview of collaborative robotic manipulation in multi-robot systems. *Annual reviews in control*. 2020. Vol. 49. P. 113–127. DOI: 10.1016/j.arcontrol.2020.02.002 (дата звернення: 05.06.2025).
49. Wooldridge M. Agent-based software engineering. *IEE proceedings – software engineering*. 1997. Vol. 144, issue 1. DOI: 10.1049/ip-sen:19971026 (дата звернення: 05.06.2025).
50. Refonaa J., Porselvi A., Jany Shabu S. L., Santhosh Krishna B. V., Siddiquee Kazy Noor-E-Alam. Characterisation of intelligent autonomous agents inspired by biological theory in cognitive environment. *Mobile information systems*. 2022. Vol. 2022. P. 1–7. DOI: 10.1155/2022/4931194 (дата звернення: 05.06.2025).
51. Hofmann P., Urbach N., Lanzl J., Desouza K. AI-enabled information systems: teaming up with intelligent agents in networked business. *Electronic markets*. 2024. Vol. 34, no. 1. Article 52. DOI: 10.1007/s12525-024-00734-y (дата звернення: 06.06.2025).
52. Bose R. Intelligent agents framework for developing knowledge-based decision support systems for collaborative organizational processes. *Expert systems with applications*. 1996. Vol. 11, no. 3. P. 247–261. DOI: 10.1016/s0957-4174(96)00042-5 (дата звернення: 06.06.2025).
53. Bond A. H. A computational model for organizations of cooperating intelligent agents. *ACM SIGOIS Bulletin*. 1990. Vol. 11, issue 2–3. P. 21–30. DOI: 10.1145/91478.91483 (дата звернення: 06.06.2025).
54. Jiang F., Dong L., Peng Y., Wang K., Yang K., Pan C., Niyato D., Dobre O. A. Large language model enhanced multi-agent systems for 6G communications. *IEEE wireless communications*. 2024. Vol. 32, issue 6. P. 48–55. DOI: 10.1109/mwc.016.2300600 (дата звернення: 06.06.2025).
55. Jimenez-Romero C., Yegenoglu A., Blum C. Multi-agent systems powered by large language models: applications in swarm intelligence. *Frontiers in artificial intelligence*. 2025. Vol. 8. DOI: 10.3389/frai.2025.1593017 (дата звернення: 06.06.2025).
56. Dada E. G., Joseph S. B., Oyewola D., Fadele A. A. Application of grey wolf optimization algorithm: recent trends, issues, and possible horizons. *Gazi university journal of science*. 2021. Vol. 35, issue 2. P. 485–504. DOI: 10.35378/gujs.820885 (дата звернення: 05.06.2025).
57. Wang Y., Chen H., Xie L., Liu J., Zhang L., Yu J. Swarm autonomy: from agent functionalization to machine intelligence. *Advanced materials*. 2024. Vol. 37, issue 2. DOI: 10.1002/adma.202312956 (дата звернення: 10.06.2025).
58. Qiu Y., Yang X., Chen S. An improved gray wolf optimization algorithm solving to functional optimization and engineering design problems. *Scientific reports*. 2024. Vol. 14, issue 1. DOI: 10.1038/s41598-024-64526-2 (дата звернення: 05.06.2025).
59. Águila-León J., Chiñas-Palacios C., Vargas-Salgado, C., Hurtado-Perez, E., García. E. X. M. Particle swarm optimization, genetic algorithm and grey wolf optimizer algorithms performance comparative for a DC-DC boost converter PID controller. *Advances in science, technology and engineering systems journal*. 2021. Vol. 6, issue 1. P. 619–625. DOI: 10.25046/aj060167 (дата звернення: 05.06.2025).
60. Abbas I. A., Mustafa M. K. A review of adaptive tuning of PID-controller: optimization techniques and applications. *International journal of nonlinear analysis and applications*. 2024. Vol. 15, issue 2. P. 29–37. DOI: 10.22075/ijnaa.2023.21415.4024 (дата звернення: 05.06.2025).
61. Pace F., Raftogianni A., Godio A. A comparative analysis of three computational-intelligence metaheuristic methods for the optimization of TDEM data. *Pure and applied geophysics*. 2022. Vol. 179, issue 2. DOI: 10.1007/s00024-022-03166-x (дата звернення: 05.06.2025).
62. Dhruva S. Review of grey wolf optimizer. *Neural Computing and Applications*. 2024. Vol. 36. P. 2713–2735. DOI: https://www.researchgate.net/publication/380364735_Review_of_Grey_Wolf_Optimizer (дата звернення: 05.06.2025).
63. Dong L., Xianfeng Y., Bingshuo Y., Yong S., Qingyang X., Xiongyan Y.An improved grey wolf optimization with multi-strategy ensemble for robot path planning. *Sensors*. 2022. Vol. 22, issue 18. Article 6843. DOI: 10.3390/s22186843 (дата звернення: 05.06.2025).
64. Ou Y., Yin P., Mo L. An improved grey wolf optimizer and its application in robot path planning. *Biomimetics*. 2023. Vol. 8, no. 1. P. 84. DOI: 10.3390/biomimetics8010084 (дата звернення: 05.06.2025).
65. Widians J. A., Wardoyo R., Hartati S. A hybrid ant colony and grey wolf optimization algorithm for exploitation-exploration balance. *Emerging science journal*. 2024. Vol. 8, no. 4. P. 1642–1654. DOI: 10.28991/esj-2024-08-04-023 (дата звернення: 05.06.2025).
66. Rafi T. H., Shubair R. M., Farhan F., Hoque Md. Z., Quayyum F. M. Recent advances in computer-aided medical diagnosis using machine learning algorithms with optimization techniques. *IEEE access*. 2021. Vol. 9. P. 137847–137868. DOI: 10.1109/access.2021.3108892 (дата звернення: 05.06.2025).
67. Nassef A. M., Abdelkareem M. A., Maghrabie H. M., Baroutaji A. Hybrid metaheuristic algorithms: a recent comprehensive review with bibliometric analysis. *International journal of electrical and computer engineering (IJECE)*. 2024. Vol. 14, issue 6. Article 7022. DOI: 10.11591/ijece.v14i6.pp7022-7035 (дата звернення: 05.06.2025).
68. Ghalambaz M., Jalilzadeh Y. R., Davami A. H. Building energy optimization using Grey Wolf Optimizer (GWO). *Case studies in thermal engineering*. 2021. Vol. 27. Article 101250. DOI: 10.1016/j.csite.2021.101250 (дата звернення: 05.06.2025).
69. Nayak G. K., Panigrahi T. K., Sahoo A. K. A novel modified random walk grey wolf optimisation approach for non-smooth and non-convex economic load dispatch. *International journal of innovative computing and applications*. 2022. Vol. 13, no. 2. P. 59–78. DOI: 10.1504/ijica.2022.10047889 (дата звернення: 05.06.2025).
70. Uz M. E. Optimal design of multi-storey buildings with tuned mass dampers using genetic algorithms and grey wolf optimization. *Journal of intelligent & fuzzy systems*. 2022. Vol. 43, issue 1. P. 1553–1567. DOI: 10.3233/jifs-212553 (дата звернення: 05.06.2025).
71. Liu J., Liu Y., Ding Y. Research and optimization of task scheduling algorithm based on heterogeneous multi-core processor. *Cluster computing*. 2024. Vol. 27. P. 13435–13453. DOI: 10.1007/s10586-024-04606-0 (дата звернення: 05.06.2025).
72. Abdullahi Y. U., Rajan J., Swaminathan J., Adedeji W. O. Coupled taguchi-pareto-box behnken design-grey wolf optimization methods for optimization decisions when boring IS 2062 E250 steel plates on

CNC machine. *Engineering access*. 2022. Vol. 10, no. 1. P. 28–41. DOI: https://www.researchgate.net/publication/378469471_Coupled_Taguchi-Pareto-Box_Behnken_Design-Grey_Wolf_Optimization_Methods_for_Optimization_Decisions_when_Boring_IS_2062_E250_Steel_Plates_on_CNC_Machine (дата звернення: 05.06.2025).

73. Peng Q., Wu H., Li N., Wang F. A dynamic task allocation method for unmanned aerial vehicle swarm based on wolf pack labor division model. *IEEE transactions on emerging topics in computational intelligence*. 2024. Vol. 8, issue 6. P. 4075–4089. DOI: 10.1109/tetci.2024.3386614 (дата звернення: 05.06.2025).
74. Dagal I., AL-Wesabi I., Harrison A., Mbasso W. F., Hourani A. O., Zaitsev I. Hierarchical multi step Gray Wolf optimization algorithm for energy systems. *Scientific reports*. 2025. Vol. 15. Article 8973. DOI: 10.1038/s41598-025-92983-w (дата звернення: 05.06.2025).
75. Rybitskyi O. M., Golian V. V., Golian N. V., Dudar Z. V., Kalynychenko O. V., Nikitin D. M Using obd-2 technology for vehicle diagnostic and using it in the information system. *Bulletin of National Technical University "KhPI". Series: System analysis, control and information technologies*. Kharkiv : NTU «KhPI», 2023. No. 1 (9). P. 97–103. DOI: 10.20998/2079-0023.2023.01.15 (дата звернення: 05.06.2025).
76. Nikitin D. Specification formalization of state charts for complex system management. *Bulletin of National Technical University "KhPI". Series: System analysis, control and information technologies*. Kharkiv : NTU «KhPI», 2023. No. 1 (9). P. 104–109. DOI: 10.20998/2079-0023.2023.01.16 (дата звернення: 05.06.2025).
77. Нікуліна О. М., Северин В. П., Кондратов О. М., Рекова Н. Ю. Аналіз інформаційних технологій длядистанційної ідентифікації динамічних об’єктів. *Вісник Національного технічного університету «ХПІ». Серія: Системний аналіз, управління та інформаційні технології*. Kharkiv : NTU «KhPI», 2023. № 1 (9). P. 110–115. DOI: 10.20998/2079-0023.2023.01.17 (дата звернення: 05.06.2025).
78. Dada E., Joseph S. B., Oyewola D., Fadele A. A. Application of grey wolf optimization algorithm: recent trends, issues, and possible horizons. *Gazi university journal of science*. 2021. Vol. 35, issue 2. P. 485–504. DOI: 10.35378/gujs.820885 (дата звернення: 05.06.2025).
79. Hashem M. H., Abdullah H. S., Ghathwan K. I. Grey wolf optimization algorithm: a survey. *Iraqi journal of science*. 2023. Vol. 64, no. 11. P. 5964–5984. DOI: 10.24996/ijs.2023.64.11.40 (дата звернення: 05.06.2025).
80. Sharma I., Kumar V., Sharma S. A comprehensive survey on grey wolf optimization. *Recent advances in computer science and communications*. 2022. Vol. 15, no. 3. P. 323–333. DOI: 10.2174/2666255813999201007165454 (дата звернення: 05.06.2025).
81. Jiang J., Sun Z., Jiang X., Jin S., Jiang Y., Fan B. VGWO: variant grey wolf optimizer with high accuracy and low time complexity. *Computers, materials & continua*. 2023. Vol. 77, issue 2, P. 1617–1644. DOI: 10.32604/cmc.2023.041973 (дата звернення: 05.06.2025).
82. Yu X., Xu WangYing, Wu X., Wang X. Reinforced exploitation and exploration grey wolf optimizer for numerical and real-world optimization problems. *Applied intelligence*. 2021. Vol. 52, issue 8. P. 8412–8427. DOI: 10.1007/s10489-021-02795-4 (дата звернення: 05.06.2025).
83. Qin H., Meng T., Cao Y. Fuzzy strategy grey wolf optimizer for complex multimodal optimization problems. *Sensors*. 2022. Vol. 22, no. 17. Article 6420. DOI: 10.3390/s22176420 (дата звернення: 05.06.2025).
84. Widians J. A., Wardoyo R., Hartati S. A hybrid ant colony and grey wolf optimization algorithm for exploitation-exploration balance. *Emerging science journal*. 2024. Vol. 8, no. 4. P. 1642–1654. DOI: 10.28991/esj-2024-08-04-023 (дата звернення: 05.06.2025).
85. Singh N. A modified variant of grey wolf optimizer. *Scientia iranica*. 2018. Vol. 27. P. 1450–1466. DOI: 10.24200/sci.2018.50122.1523 (дата звернення: 05.06.2025).
86. Tu B., Wang F., Huo Y., Wang X. A hybrid algorithm of grey wolf optimizer and harris hawks optimization for solving global optimization problems with improved convergence performance. *Scientific reports*. 2023. Vol. 13, no. 1. Article 22909. DOI: 10.1038/s41598-023-49754-2 (дата звернення: 05.06.2025).
87. Akbari E., Rahimnejad A., Gadsden S. A. A greedy non-hierarchical grey wolf optimizer for real-world optimization. *Electronics letters*. 2021. Vol. 57, no. 13. P. 499–501. DOI: 10.1049/ell2.12176 (дата звернення: 05.06.2025).
88. Lei W., Jiawei W., Zezhou M. Enhancing grey wolf optimizer with levy flight for engineering applications. *IEEE access*. 2023. Vol. 11. P. 74865–74897. DOI: 10.1109/access.2023.3295242 (дата звернення: 05.08.2025).
89. Ye Z., Huang R., Zhou W., Wang M., Cai T., He Q., Zhang P., Zhang Y. Hybrid rice optimization algorithm inspired grey wolf optimizer for high-dimensional feature selection. *Scientific reports*. 2024. Vol. 14, no. 1. Article 30741. DOI: 10.1038/s41598-024-80648-z (дата звернення: 05.06.2025).
90. Keshari S. K., Kansal V., Kumar S. A cluster based intelligent method to manage load of controllers in sdn-iot networks for smart cities. *Scalable computing: practice and experience*. 2021. Vol. 22, no. 2. P. 247–257. DOI: 10.12694/scpe.v22i2.1912 (дата звернення: 30.07.2025).
91. Liu X., Wang Y., Zhou M. Dimensional learning strategy-based grey wolf optimizer for solving the global optimization problem. *Computational intelligence and neuroscience*. 2022. P. 1–31. DOI: 10.1155/2022/3603607 (дата звернення: 30.07.2025).
92. Hu C., Zhou H., Lv S. Clustering based on gray wolf optimization algorithm for internet of things over wireless nodes. *International journal of advanced computer science and applications*. 2023. Vol. 14, no. 6. P. 334–341. DOI: 10.14569/ijacsa.2023.0140637 (дата звернення: 30.07.2025).
93. Shaikh M. S., Wang C., Xie S., Zheng G., Dong X., Qiu S., Ahmad M. A., Raj S. Coverage and connectivity maximization for wireless sensor networks using improved chaotic grey wolf optimization. *Scientific reports*. 2025. Vol. 15, no. 1. Article 15706. DOI: 10.1038/s41598-025-00184-2 (дата звернення: 30.07.2025).
94. Nadimi-Shahraki M. H., Zamani H., Varzaneh Z. A., Sadiq A. S., Mirjalili S. A systematic review of applying grey wolf optimizer, its variants, and its developments in different internet of things applications. *Internet of things*. 2024. Vol. 26. Article 101135. DOI: 10.1016/j.iot.2024.101135 (дата звернення: 30.07.2025).
95. Singh S., Nikolovski S., Chakrabarti P. GWLBC: gray wolf optimization based load balanced clustering for sustainable wsns in smart city environment. *Sensors*. 2022. Vol. 22, no. 19. Article 7113. DOI: 10.3390/s22197113 (дата звернення: 30.07.2025).
96. Alsadie D., Alsulami M. Modified grey wolf optimization for energy-efficient internet of things task scheduling in fog computing. *Scientific reports*. 2025. Vol. 15, no. 1. P. 1–16. DOI: 10.1038/s41598-025-99837-5 (дата звернення: 30.07.2025).
97. Yakovlev S. V. The method of artificial space dilation in problems of optimal packing of geometric objects. *Cybernetics and systems analysis*. 2017. Vol. 53, no. 5. P. 725–731. DOI: 10.1007/s10559-017-9974-y (дата звернення: 26.08.2025).
98. Stoyan Y. G., Yaskov G. N. Packing identical spheres into a cylinder. *International transactions in operational research*. 2010. Vol. 17, no. 1. P. 51–70. DOI: 10.1111/j.1475-3995.2009.00733.x (дата звернення: 26.08.2025).
99. Stoyan Y., Yaskov G. Packing equal circles into a circle with circular prohibited areas. *International journal of computer mathematics*. 2012. Vol. 89, no. 10. P. 1355–1369. DOI: 10.1080/00207160.2012.685468 (дата звернення: 26.08.2025).
100. Stoyan Y., Yaskov G., Romanova T., Litvinchev I., Yakovlev S., Cantú J. M. V. Optimized packing multidimensional hyperspheres: a unified approach. *Mathematical biosciences and engineering*. 2020. Vol. 17, no. 6. P. 6601–6630. DOI: 10.3934/mbe.2020344 (дата звернення: 26.08.2025).
101. Yakovlev S., Kartashov O., Pichugina O., Korobchynskyi K. Genetic algorithms for solving combinatorial mass balancing problem. *2019 IEEE 2nd Ukraine conference on electrical and computer engineering (UKRCON)*. 2019. Lviv, Ukraine. P 1061–1064. DOI: 10.1109/ukrcon.2019.8879938 (дата звернення: 26.08.2025).
102. Yakovlev S., Kartashov O., Korobchynskyi K., Skripka B. Numerical results of variable radii method in the unequal circles packing problem. *2019 IEEE 15th international conference on the experience of designing and application of CAD systems (CADSM)*. 2019. Polyana, Ukraine. P. 1–4. DOI: 10.1109/cadsm.2019.8779288 (дата звернення: 26.08.2025).
103. Stoyan Y., Chugay A. Packing cylinders and rectangular parallelepipeds with distances between them into a given region.

European journal of operational research. 2009. Vol. 197, no. 2. P. 446–455. URL: https://doi.org/10.1016/j.ejor.2008.07.003 (дата звернення: 26.08.2025).

104. Stoyan Y., Pankratov A., Romanova T., Fasano G., Pintér J. D., Stoian Y. E., Chugay A. Optimized packings in space engineering applications: part I. *Springer optimization and its applications*. Cham, 2019. P. 395–437. DOI: 10.1007/978-3-030-10501-3_15 (дата звернення: 26.08.2025).
105. Stoyan Y., Grebennik I., Romanova T., Kovalenko A. Optimized packings in space engineering applications: part II. *Springer optimization and its applications*. Cham, 2019. P. 439–457. DOI: 10.1007/978-3-030-10501-3_16 (дата звернення: 26.08.2025).
106. Yakovlev S. Configuration spaces of geometric objects with their applications in packing, layout and covering problems. Advances in intelligent systems and computing. *Cham*. 2019. P. 122–132. DOI: 10.1007/978-3-030-26474-1_9 (дата звернення: 26.08.2025).

References (transliterated)

1. Nguyen L. V. Swarm Intelligence-Based Multi-Robotics: A Comprehensive Review. *AppliedMath*. 2024, vol. 4, no. 4, pp. 1192–1210. DOI: 10.3390/appliedmath4040064 (accessed 05.06.2025).
2. Xu M., Cao L., Lu D., Hu Z., Yue Y.Application of swarm intelligence optimization algorithms in image processing: a comprehensive review of analysis, synthesis, and. *Biomimetics*. 2023, vol. 8, no. 2, article 235. DOI: 10.3390/biomimetics8020235 (accessed 05.06.2025).
3. Lui H.-P., Phoa F. K. H., Chen-Burger Y.-H., Lin S.-P. An efficient swarm intelligence approach to the optimization on high-dimensional solutions with cross-dimensional constraints, with applications in supply chain managemenl. *Frontiers in computational neuroscience*. 2024, vol. 18. DOI: 10.3389/fncom.2024.1283974 (accessed 05.06.2025).
4. Nasir M., Sadollah A., Mirjalili S., Mansouri S. A., Safaraliev M., Jordehi A. R. A comprehensive review on applications of grey wolf optimizer in energy systems. *Archives of computational methods in engineering*. 2024, vol. 32, pp. 2279–2319 DOI: 10.1007/s11831-024-10214-3 (accessed 05.06.2025).
5. Negi G., Kumar A., Pant S., Ram M. GWO: a review and applicationsl. *International journal of system assurance engineering and management*. 2020, vol. 4, issue 2, pp. 241–256. DOI: 10.1007/s13198-020-00995-8 (accessed 05.06.2025).
6. Makhadmeh S. N., Al-Betar M. A., Doush I. A., Awadallah M., Kassaymeh S., Mirjalili S., Zitar R. A. Recent advances in grey wolf optimizer, its versions and applications: review *IEEE access*. 2023, vol. 12, pp. 22991–23028. DOI: 10.1109/access.2023.3304889 (accessed 05.06.2025).
7. Deep K., Gupta S., Mirjalili S. Accelerated grey wolf optimiser for continuous optimisation problems. *International journal of swarm intelligence*. 2020, vol. 5, no. 1, pp. 22–59. DOI: 10.1504/ijsi.2020.10027788 (accessed 05.06.2025).
8. Hashem M. H., Abdullah H. S., Ghathwan K. I. Grey wolf optimization algorithm: a survey. *Iraqi journal of science*. 2023, vol. 64, no. 1, pp. 5964–5984. DOI: 10.24996/ijs.2023.64.11.40 (accessed 05.06.2025).
9. Zvornicanin E. Grey wolf optimization algorithm. DOI: https://www.baeldung.com/cs/grey-wolf-optimization (accessed 05.06.2025).
10. Shafronenko, A., Bodyanskiy Y. Adaptyvnyi pidkhid do nechitkoi klasteryzatsii na osnovi evoliutsiinoi optymizatsii alhorytmu sirykh vovkiv [Adaptive fuzzy clustering approach based on evolutionary optimization of the gray wolf algorithm. *Zbirnyk naukovykh prats Kharkivskoho natsionalnoho universytetu Povitrianykh Syl* [Scientific Works of Kharkiv National Air Force University]. 2023, no 1 (75), pp. 77–81. DOI: 10.30748/zhups.2023.75.11. (In Ukr.).
11. Jürgens U. M., Grinko M., Szameitat A., Hieber L., Fischbach R., Hunziker M. Managing wolves is managing narratives: views of wolves and nature shape people's proposals for navigating human-wolf relations. *Human ecology*. 2023, vol. 51, pp. 35–57. DOI: 10.1007/s10745-022-00366-w (accessed 05.06.2025).
12. Rezaei F., Safavi H. R., Abd Elaziz M., El-Sappagh S. H. A., Al-Betar M. A., Abuhmed T. An enhanced grey wolf optimizer with a velocity-aided global search mechanism. *Mathematics*. 2022, vol. 10, issue 3, article 351. DOI: 10.3390/math10030351 (accessed 05.06.2025).
13. Li K., Li S., Huang Z., Zhang M., Xu Z. Grey Wolf Optimization algorithm based on Cauchy-Gaussian mutation and improved search strategy. *Scientific reports*. 2022, vol. 12, no. 1, article 18961. DOI: 10.1038/s41598-022-23713-9 (accessed 05.06.2025).
14. Silaa M. Y., Barambones O., Bencherif A., Rahmani A. A new mppt-based extended grey wolf optimizer for stand-alone PV system: A performance evaluation versus four smart MPPT techniques in diverse scenarios. *Inventions*. 2023, vol. 8, issue 6, article 142. DOI: 10.3390/inventions8060142 (accessed 05.06.2025).
15. Ou Y., Qin F., Zhou K.-Q., Yin P.-F., Mo L.-P., Zain A. M. An improved grey wolf optimizer with multi-strategies coverage in wireless sensor networks. *Symmetry*. 2024, vol. 16, issue 3, article 286. DOI: 10.3390/sym16030286 (accessed 05.06.2025).
16. Bhatt B., Sharma H., Arora K., Joshi G. P., Shrestha B. Levy flight-based improved grey wolf optimization: a solution for various engineering problems.*Mathematics*. 2023, vol. 11, issue 7, articl. 1745. DOI: 10.3390/math11071745 (accessed 05.06.2025).
17. Sharma I., Kumar V., Sharma S. A comprehensive survey on grey wolf optimization. *Recent advances in computer science and communications*. 2020, vol. 13. DOI: 10.2174/2666255813999201007165454 (accessed 05.06.2025).
18. Shial G., Sahoo S., Panigrahi S. An improved GWO algorithm for data clustering. *Communications in computer and information science*. Cham, 2022, pp. 79–90. DOI: 10.1007/978-3-031-21750-0_7 (accessed 05.06.2025).
19. Vargas M., Cortes D., Ramirez-Salinas M. A., Villa-Vargas L. A., Lopez A. Random exploration and attraction of the best in swarm intelligence algorithms. *Applied sciences*. 2024, vol. 14, issue 23, article 11116. DOI: 10.3390/app142311116 (accessed 05.06.2025).
20. Qiu Y., Yang X., Chen S. An improved gray wolf optimization algorithm solving to functional optimization and engineering design problems. *Scientific reports*. 2024, vol. 14, no. 1, article 14190. DOI: 10.1038/s41598-024-64526-2 (accessed 05.06.2025).
21. Rudowsky I. Intelligent agents. *Communications of the association for information systems*. 2004, vol. 14, pp. 275–290. DOI: 10.17705/1cais.01414 (accessed 05.06.2025).
22. Jeapes B. Neural intelligent agents. *Online and CD-Rom Review*. 1996, vol. 20, no. 5, pp. 260–262. DOI: 10.1108/eb024592 (accessed 10.06.2025).
23. Sycara K., Pannu A., Zeng D. D. Distributed intelligent agents. *IEEE expert*. 1996, vol. 11, no. 6, pp. 36–46. DOI: 10.1109/64.546581 (accessed 10.06.2025).
24. Wong A. Intelligent software agents. *Computer communications*. 2000, vol. 23, no. 7, pp. 695–696. DOI: 10.1016/s0140-3664(99)00186-3 (accessed 10.06.2025).
25. Vasilakos A. V. Intelligent information agents. *Computer communications*. 2000, vol. 23, no. 18, article 1790. DOI: 10.1016/s0140-3664(00)00211-5 (accessed 10.06.2025).
26. Hagras H., Callaghan V., Colley M. Intelligent embedded agents. *Information sciences*. 2005, vol. 171, no. 4, pp. 289–292. DOI: 10.1016/j.ins.2004.09.006 (accessed 10.06.2025).
27. Edmonds B. Modeling socially intelligent agents. *Applied artificial intelligence*. 1998, vol. 12, no. 7–8, pp. 677–699. DOI: 10.1080/088395198117587 (accessed 10.06.2025).
28. Mattern S. Mapping's intelligent agents. *Places journal*. 2017, article 2017. DOI: 10.22269/170926 (accessed 10.06.2025).
29. Nowostawski M., Bush G., Purvis M., Cranefield S. A multi-level approach and infrastructure for agent-oriented software development. *The first international joint conference*, Bologna, Italy, 15–19 July 2002. New York, New York, USA, 2002, DOI: 10.1145/544741.544763 (accessed 05.06.2025).
30. Lopes Y. S., Cortés M. I., Gonçalves E. J. T., Oliveira R. JAMDER: JADE to multi-agent systems development resource. *ADCAIJ: advances in distributed computing and artificial intelligence journal*. 2018, vol. 7, no. 3, article 63. DOI: 10.14201/adcaij2018736398 (accessed 05.06.2025).
31. AlShabi M., Ghenai C., Bettayeb M., Ahmad F. F., El Haj Assad M.Multi-group grey wolf optimizer (MG-GWO) for estimating photovoltaic solar cell model. *Journal of thermal analysis and calorimetry*. 2020, vol. 144, issue 5, pp 1655–1670. DOI: 10.1007/s10973-020-09895-2 (accessed 05.06.2025).
32. Li J., Huang J., Liu J., Zheng T. Human-AI cooperation: modes and their effects on attitudes. *Telematics and informatics*. 2022, Vol. 72, article 101862. DOI: 10.1016/j.tele.2022.101862 (accessed 05.06.2025).
33. Zhou X., Shi G., Zhang J. Improved grey wolf algorithm: A method

for UAV path planning. *Drones*. 2024, vol. 8, no. 11, p. 675. DOI: 10.3390/drones8110675 (accessed 05.06.2025).

34. Liu Q., Wang H. UAV 3D path planning based on improved grey wolf optimization algorithm. *Frontiers in computing and intelligent systems*. 2023, vol. 3, no. 1, pp. 113–116. DOI: 10.54097/fcis.v3i1.6344 (accessed 05.06.2025).
35. Hou Y., Gao H., Wang Z., Du C. Improved grey wolf optimization algorithm and application. *Sensors*. 2022, vol. 22, no. 10, article 3810. DOI: 10.3390/s22103810 (accessed 05.06.2025).
36. Zhang X., Lin Q., Mao W., Liu S., Dou Z., Liu G. Hybrid particle swarm and grey wolf optimizer and its application to clustering optimization. *Applied soft computing*. 2020, article 107061. DOI: 10.1016/j.asoc.2020.107061 (accessed 05.06.2025).
37. Hamdan A., Tahboush M., Adawy M., Alwada'n T., Ghwanmeh S., Moath H. Phishing detection using grey wolf and particle swarm optimizer. *International journal of electrical and computer engineering (IJECE)*. 2024, vol. 14, no. 5, pp. 5961–5969. DOI: 10.11591/ijece.v14i5.pp5961-5969 (accessed 05.06.2025).
38. Soban S., Sireesha R., Pavithra G., Badonia S.Grey wolf optimizer algorithm for multi-objective optimal power flow. *Journal of intelligent systems and internet of things*. 2024, vol. 12, no. 1, pp. 20–32. DOI: 10.54216/jisiot.120102 (accessed 05.06.2025).
39. Zhang L., Sun Y., Barth A., Ma O. Decentralized control of multi-robot system in cooperative object transportation using deep reinforcement learning. *IEEE access*. 2020, vol. 8, pp. 184109–184119. DOI: 10.1109/access.2020.3025287 (accessed 05.06.2025).
40. Dai W., Lu H., Xiao J., Zeng Zhiwen, Zheng Zhiqiang. Multi-Robot dynamic task allocation for exploration and destruction. *Journal of intelligent & robotic systems*. 2019, vol. 98, no. 2, pp. 455–479. DOI: 10.1007/s10846-019-01081-3 (accessed 05.06.2025).
41. Verma J. K., Ranga V. Multi-Robot coordination analysis, taxonomy, challenges and future scope. *Journal of intelligent & robotic systems*. 2021, vol. 102, no. 1. DOI: 10.1007/s10846-021-01378-2 (accessed 05.06.2025).
42. Sung Y., Budhiraja A. K., Williams R. K., Tokekar P. Distributed assignment with limited communication for multi-robot multi-target tracking. *Autonomous robots*. 2019, vol. 44, no. 1, pp. 57–73. DOI: 10.1007/s10514-019-09856-1 (accessed 05.06.2025).
43. Otte M., Kuhlman M. J., Sofge D. Auctions for multi-robot task allocation in communication limited environments. *Autonomous robots*. 2019, vol. 44, no. 3–4, pp. 547–584. DOI: 10.1007/s10514-019-09828-5 (accessed 05.06.2025).
44. Queralta J. P. et al. Collaborative multi-robot search and rescue: planning, coordination, perception, and active vision. *IEEE access*. 2020, vol. 8, pp. 191617–191643. DOI: 10.1109/access.2020.3030190 (accessed 05.06.2025).
45. Motes J., Sandström R., Lee H., Thomas S., Amato N. M. Multi-Robot task and motion planning with subtask dependencies. *IEEE robotics and automation letters*. 2020, vol. 5, no. 2, pp. 3338–3345. DOI: 10.1109/lra.2020.2976329 (accessed 05.06.2025).
46. Li J., Yang F. Task assignment strategy for multi-robot based on improved Grey Wolf Optimizer. *Journal of ambient intelligence and humanized computing*. 2020, vol. 11, no. 12, pp. 6319–6335. DOI: 10.1007/s12652-020-02224-3 (accessed 05.06.2025).
47. Su Y., Wang Q., Sun C. Self-triggered consensus control for linear multi-agent systems with input saturation. *IEEE/CAA journal of automatica sinica*. 2020, vol. 7, no. 1, pp. 150–157. DOI: 10.1109/jas.2019.1911837 (accessed 05.06.2025).
48. Feng Z., Hu G., Sun Y., Soon J. An overview of collaborative robotic manipulation in multi-robot systems. *Annual reviews in control*. 2020, vol. 49, pp. 113–127. DOI: 10.1016/j.arcontrol.2020.02.002 (accessed 05.06.2025).
49. Wooldridge M. Agent-based software engineering. *IEE proceedings software engineering*. 1997, vol. 144, no. 1. DOI: 10.1049/ip-sen:19971026 (accessed 05.06.2025).
50. Refonaa J., Porselvi A., Jany Shabu S. L., Santhosh Krishna B. V., Siddiquee Kazy Noor-E-Alam. Characterisation of intelligent autonomous agents inspired by biological theory in cognitive environment. *Mobile information systems*. 2022, vol. 2022, pp. 1–7. DOI: 10.1155/2022/4931194 (accessed 05.06.2025).
51. Hofmann P., Urbach N., Lanzl J., Desouza K. AI-enabled information systems: teaming up with intelligent agents in networked business. *Electronic markets*. 2024, vol. 34, no. 1, article 52. DOI: 10.1007/s12525-024-00734-y (accessed 06.06.2025).
52. Bose R. Intelligent agents framework for developing knowledge-based decision support systems for collaborative organizational processes. *Expert systems with applications*. 1996, vol. 11, no. 3, pp. 247–261. DOI: 10.1016/s0957-4174(96)00042-5 (accessed 06.06.2025).
53. Bond A. H. A computational model for organizations of cooperating intelligent agents. *ACM SIGOIS Bulletin*. 1990, vol. 11, issue 2–3, pp. 21–30. DOI: 10.1145/91478.91483 (accessed 06.06.2025).
54. Jiang F., Dong L., Peng Y., Wang K., Yang K., Pan C., Niyato D., Dobre O. A. Large language model enhanced multi-agent systems for 6G communications. *IEEE wireless communications*. 2024, vol. 32, issue 6, pp. 48–55. DOI: 10.1109/mwc.016.2300600 (accessed 06.06.2025).
55. Jimenez-Romero C., Yegenoglu A., Blum C. Multi-agent systems powered by large language models: applications in swarm intelligence. *Frontiers in artificial intelligence*. 2025, vol. 8. DOI: 10.3389/frai.2025.1593017 (accessed 06.06.2025).
56. Dada E. G., Joseph S. B., Oyewola D., Fadele A. A. Application of grey wolf optimization algorithm: recent trends, issues, and possible horizons. *Gazi university journal of science*. 2021, vol. 35, issue 2, pp. 485–504. DOI: 10.35378/gujs.820885 (accessed 05.06.2025).
57. Wang Y., Chen H., Xie L., Liu J., Zhang L., Yu J. Swarm autonomy: from agent functionalization to machine intelligence. *Advanced materials*. 2024, vol. 37, issue 2. DOI: 10.1002/adma.202312956 (accessed 10.06.2025).
58. Qiu Y., Yang X., Chen S. An improved gray wolf optimization algorithm solving to functional optimization and engineering design problems. *Scientific reports*. 2024, vol. 14, issue 1. DOI: 10.1038/s41598-024-64526-2 (accessed 05.06.2025).
59. Águila-León J., Chiñas-Palacios C., Vargas-Salgado, C., Hurtado-Perez, E., García. E. X. M. Particle swarm optimization, genetic algorithm and grey wolf optimizer algorithms performance comparative for a DC-DC boost converter PID controller. *Advances in science, technology and engineering systems journal*. 2021, vol. 6, issue 1, pp. 619–625. DOI: 10.25046/aj060167 (accessed 05.06.2025).
60. Abbas I. A., Mustafa M. K. A review of adaptive tuning of PID-controller: optimization techniques and applications. *International journal of nonlinear analysis and applications*. 2024, vol. 15, issue 2, pp. 29–37. DOI: 10.22075/ijnaa.2023.21415.4024 (accessed 05.06.2025).
61. Pace F., Raftogianni A., Godio A. A comparative analysis of three computational-intelligence metaheuristic methods for the optimization of TDEM data. *Pure and applied geophysics*. 2022, vol. 179, issue 2. DOI: 10.1007/s00024-022-03166-x (accessed 05.06.2025).
62. Dhruva S. Review of grey wolf optimizer. *Neural Computing and Applications*. 2024, vol. 36, pp. 2713–2735. DOI: https://www.researchgate.net/publication/380364735_Review_of_Grey_Wolf_Optimizer (accessed 05.06.2025).
63. Dong L., Xianfeng Y., Bingshuo Y., Yong S., Qingyang X., Xiongyan Y.An improved grey wolf optimization with multi-strategy ensemble for robot path planning. *Sensors*. 2022, vol. 22, issue 18, article 6843. DOI: 10.3390/s22186843 (accessed 05.06.2025).
64. Ou Y., Yin P., Mo L. An improved grey wolf optimizer and its application in robot path planning. *Biomimetics*. 2023, vol. 8, no. 1, p. 84. DOI: 10.3390/biomimetics8010084 (accessed 05.06.2025).
65. Widians J. A., Wardoyo R., Hartati S. A hybrid ant colony and grey wolf optimization algorithm for exploitation-exploration balance. *Emerging science journal*. 2024, vol. 8, no. 4, pp. 1642–1654. DOI: 10.28991/esj-2024-08-04-023 (accessed 05.06.2025).
66. Rafi T. H., Shubair R. M., Farhan F., Hoque Md. Z., Quayyum F. M. Recent advances in computer-aided medical diagnosis using machine learning algorithms with optimization techniques. *IEEE access*. 2021, vol. 9, pp. 137847–137868. DOI: 10.1109/access.2021.3108892 (accessed 05.06.2025).
67. Nassef A. M., Abdelkareem M. A., Maghrabie H. M., Baroutaji A. Hybrid metaheuristic algorithms: a recent comprehensive review with bibliometric analysis. *International journal of electrical and computer engineering (IJECE)*. 2024, vol. 14, issue 6, article 7022. DOI: 10.11591/ijece.v14i6.pp7022-7035 (accessed 05.06.2025).
68. Ghalambaz M., Jalilzadeh Yengejeh R., Davami A. H. Building energy optimization using Grey Wolf Optimizer (GWO). *Case studies in thermal engineering*. 2021, vol. 27, article 101250. DOI: 10.1016/j.csite.2021.101250 (accessed 05.06.2025).
69. Nayak G. K., Panigrahi T. K., Sahoo A. K. A novel modified random

walk grey wolf optimisation approach for non-smooth and non-convex economic load dispatch. *International journal of innovative computing and applications*. 2022, vol. 13, no. 2, p. 59–78. DOI: 10.1504/ijica.2022.10047889 (accessed 05.06.2025).

70. Uz M. E. Optimal design of multi-storey buildings with tuned mass dampers using genetic algorithms and grey wolf optimization. *Journal of intelligent & fuzzy systems*. 2022, vol. 43, issue 1, pp. 1553–1567. DOI: 10.3233/jifs-212553 (accessed 05.06.2025).
71. Liu J., Liu Y., Ding Y. Research and optimization of task scheduling algorithm based on heterogeneous multi-core processor. *Cluster computing*. 2024, vol. 27, pp. 13435–13453 DOI: 10.1007/s10586-024-04606-0 (accessed 05.06.2025).
72. Abdullahi Y. U., Rajan J., Swaminathan J., Adedeji W. O. Coupled taguchi-pareto-box behnken design-grey wolf optimization methods for optimization decisions when boring IS 2062 E250 steel plates on CNC machine. *Engineering access.* 2022, vol. 10, no. 1, pp. 28–41. DOI: https://www.researchgate.net/publication/378469471_Coupled_Taguchi-Pareto-Box_Behnken_Design-Grey_Wolf_Optimization_Methods_for_Optimization_Decisions_when_Boring_IS_2062_E250_Steel_Plates_on_CNC_Machine (accessed 05.06.2025).
73. Peng Q., Wu H., Li N., Wang F. A dynamic task allocation method for unmanned aerial vehicle swarm based on wolf pack labor division model. *IEEE transactions on emerging topics in computational intelligence*. 2024, vol. 8, issue 6, pp. 4075–4089. DOI: 10.1109/tetci.2024.3386614 (accessed 05.06.2025).
74. Dagal I., AL-Wesabi I., Harrison A., Mbasso W. F., Hourani A. O., Zaitsev I. Hierarchical multi step Gray Wolf optimization algorithm for energy systems optimization. *Scientific reports*. 2025, vol. 15, article 8973. DOI: 10.1038/s41598-025-92983-w (accessed 05.06.2025).
75. Rybitskyi O. M., Golian V. V., Golian N. V., Dudar Z. V., Kalynychenko O. V., Nikitin D. M Using obd-2 technology for vehicle diagnostic and using it in the information system. *Bulletin of National Technical University "KhPI". Series: System analysis, control and information technologies*. Kharkiv, NTU "KhPI" Publ., 2023, no. 1 (9), pp. 97–103. DOI: 10.20998/2079-0023.2023.01.15 (accessed 05.06.2025).
76. Nikitin D. Specification formalization of state charts for complex system management. *Bulletin of National Technical University "KhPI". Series: System analysis, control and information technologies*. Kharkiv, NTU "KhPI" Publ., 2023, no. 1 (9), pp. 104–109. DOI: 10.20998/2079-0023.2023.01.16 (accessed 05.06.2025).
77. Nikulina O. M., Severyn V. P., Kondratov O. M., Rekova N. Y. Analiz informatsiinykh tekhnolohii dliadystantsiinoi identyfikatsii dynamichnykh obiektiv [Analysis of information technologies for remote identification of dynamic objects]. *Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». Seriia: Systemnyi analiz, upravlinnia ta informatsiini tekhnolohii* [Bulletin of National Technical University "KhPI". Series: System analysis, control and information technologies]. Kharkiv, NTU "KhPI" Publ., 2023, no. 1 (9), pp. 110–115. DOI: 10.20998/2079-0023.2023.01.17 (accessed 05.06.2025). (In Ukr.).
78. Dada E., Joseph S. B., Oyewola D., Fadele A. A. Application of grey wolf optimization algorithm: recent trends, issues, and possible horizons. *Gazi university journal of science.* 2021, vol. 35, issue 2. pp. 485–504. DOI: 10.35378/gujs.820885 (accessed 05.06.2025).
79. Hashem M. H., Abdullah H. S., Ghathwan K. I. Grey wolf optimization algorithm: a survey. *Iraqi journal of science*. 2023, Vol. 64, no. 11, pp. 5964–5984. DOI: 10.24996/ijs.2023.64.11.40 (accessed 05.06.2025).
80. Sharma I., Kumar V., Sharma S. A comprehensive survey on grey wolf optimization. *Recent advances in computer science and communications*. 2022, vol. 15, no. 3, pp. 323–333. DOI: 10.2174/2666255813999201007165454 (accessed 05.06.2025).
81. Jiang J., Sun Z., Jiang X., Jin S., Jiang Y., Fan B. VGWO: variant grey wolf optimizer with high accuracy and low time complexity. *Computers, materials & continua*. 2023, vol. 77, issue 2, pp. 1617–1644. DOI: 10.32604/cmc.2023.041973 (accessed 05.06.2025).
82. Yu X., Xu WangYing, Wu X., Wang X. Reinforced exploitation and exploration grey wolf optimizer for numerical and real-world optimization problems. *Applied intelligence*. 2021, vol. 52, issue 8, pp. 8412–8427. DOI: 10.1007/s10489-021-02795-4 (accessed 05.06.2025).
83. Qin H., Meng T., Cao Y. Fuzzy strategy grey wolf optimizer for complex multimodal optimization problems. *Sensors*. 2022, vol. 22, no. 17, article 6420. DOI: 10.3390/s22176420 (accessed 05.06.2025).
84. Widians J. A., Wardoyo R., Hartati S. A hybrid ant colony and grey wolf optimization algorithm for exploitation-exploration balance. *Emerging science journal*. 2024, vol. 8, no. 4, pp. 1642–1654. DOI: 10.28991/esj-2024-08-04-023 (accessed 05.06.2025).
85. Singh N. A modified variant of grey wolf optimizer. *Scientia iranica*. 2018, vol. 27, pp. 1450–1466. DOI: 10.24200/sci.2018.50122.1523 (accessed 05.06.2025).
86. Tu B., Wang F., Huo Y., Wang X. A hybrid algorithm of grey wolf optimizer and harris hawks optimization for solving global optimization problems with improved convergence performance. *Scientific reports*. 2023, vol. 13, no. 1, article 22909. DOI: 10.1038/s41598-023-49754-2 (accessed 05.06.2025).
87. Akbari E., Rahimnejad A., Gadsden S. A. A greedy non-hierarchical grey wolf optimizer for real-world optimization. *Electronics letters*. 2021, vol. 57, no. 13, pp. 499–501. DOI: 10.1049/ell2.12176 (accessed 05.06.2025).
88. Lei W., Jiawei W., Zezhou M. Enhancing grey wolf optimizer with levy flight for engineering applications. *IEEE access*. 2023, vol. 11, pp. 74865–74897. DOI: 10.1109/access.2023.3295242 (accessed 05.08.2025)
89. Ye Z., Huang R., Zhou W., Wang M., Cai T., He Q., Zhang P., Zhang Y. Hybrid rice optimization algorithm inspired grey wolf optimizer for high-dimensional feature selection. *Scientific reports*. 2024, vol. 14, no. 1, article 30741. DOI: 10.1038/s41598-024-80648-z (accessed 05.06.2025).
90. Keshari S. K., Kansal V., Kumar S. A cluster based intelligent method to manage load of controllers in sdn-iot networks for smart cities. *Scalable computing: practice and experience*. 2021, vol. 22, no. 2, pp. 247–257. DOI: 10.12694/scpe.v22i2.1912 (accessed 30.07.2025).
91. Liu X., Wang Y., Zhou M. Dimensional learning strategy-based grey wolf optimizer for solving the global optimization problem. *Computational Intelligence and Neuroscience*. 2022, pp. 1–31. DOI: 10.1155/2022/3603607 (accessed 30.07.2025).
92. Hu C., Zhou H., Lv S. Clustering based on gray wolf optimization algorithm for internet of things over wireless nodes. *International journal of advanced computer science and applications*. 2023, vol. 14, no. 6, pp. 334–341. DOI: 10.14569/ijacsa.2023.0140637 (accessed 30.07.2025).
93. Shaikh M. S., Wang C., Xie S., Zheng G., Dong X., Qiu S., Ahmad M. A., Raj S. Coverage and connectivity maximization for wireless sensor networks using improved chaotic grey wolf optimization. *Scientific reports*. 2025, vol. 15, no. 1, article 15706. DOI: 10.1038/s41598-025-00184-2 (accessed 30.07.2025)
94. Nadimi-Shahraki M. H., Zamani H., Varzaneh Z. A., Sadiq A. S., Mirjalili S. A systematic review of applying grey wolf optimizer, its variants, and its developments in different internet of things applications. *Internet of Things*. 2024, vol. 26, article 101135. DOI: 10.1016/j.iot.2024.101135 (accessed 30.07.2025)
95. Singh S., Nikolovski S., Chakrabarti P. GWLBC: gray wolf optimization based load balanced clustering for sustainable wsns in smart city environment. *Sensors.* 2022, vol. 22, no. 19, article 7113. DOI: 10.3390/s22197113 (accessed 30.07.2025)
96. Alsadie D., Alsulami M. Modified grey wolf optimization for energy-efficient internet of things task scheduling in fog computing. *Scientific Reports*. 2025, vol. 15, no. 1, pp. 1–16. DOI: 10.1038/s41598-025-99837-5 (accessed 30.07.2025).
97. Yakovlev S. V. The method of artificial space dilation in problems of optimal packing of geometric objects. *Cybernetics and systems analysis.* 2017, vol. 53, no. 5, pp. 725–731. DOI: 10.1007/s10559-017-9974-y (accessed 28.08.2025).
98. Stoyan Y. G., Yaskov G. N. Packing identical spheres into a cylinder. *International Transactions in Operational Research*. 2010, vol. 17, no. 1, pp. 51–70. DOI: 10.1111/j.1475-3995.2009.00733.x (accessed 28.08.2025).
99. Stoyan Y., Yaskov G. Packing equal circles into a circle with circular prohibited areas. *International journal of computer mathematics*. 2012, vol. 89, no.10, pp. 1355–1369. DOI: 10.1080/00207160.2012.685468 (accessed 28.08.2025).
100. Yaskov G., Romanova T., Litvinchev I., Yakovlev S., Cantú J. M. V. Optimized packing multidimensional hyperspheres: a unified approach. *Mathematical biosciences and engineering*. 2020, vol. 17,

no. 6, pp. 6601–6630. DOI: 10.3934/mbe.2020344 (accessed 28.08.2025).

101. Yakovlev S., Kartashov O., Pichugina O. та Korobchynskyi K. Genetic algorithms for solving combinatorial mass balancing problem. *2019 IEEE 2nd Ukraine conference on electrical and computer engineering (UKRCON).* Lviv, Ukraine, 2019, pp. 1061–1064. DOI: 10.1109/ukrcon.2019.8879938 (accessed 28.08.2025).
102. Yakovlev S., Kartashov O., Korobchynskyi K., Skripka B. Numerical results of variable radii method in the unequal circles packing problem. *2019 IEEE 15th international conference on the experience of designing and application of CAD systems (CADSM).* Polyana, Ukraine, 2019, pp. 1–4. DOI: 10.1109/cadsm.2019.8779288 (accessed 28.08.2025).
103. Stoyan Y., Chugay A. Packing cylinders and rectangular parallelepipeds with distances between them into a given region. *European journal of operational research*. 2009, vol. 197, no. 2, pp. 446–455. DOI: 10.1016/j.ejor.2008.07.003 (accessed 28.08.2025).
104. Stoyan Y., Pankratov A., Romanova T., Fasano G., Pintér J. D., Stoian Y. E., Chugay A. Optimized packings in space engineering applications: part I. Springer optimization and its applications. *Cham: Springer International Publishing*. 2019, pp. 395–437. DOI: 10.1007/978-3-030-10501-3_15 (accessed 28.08.2025)
105. Stoyan Y., Grebennik I., Romanova T., Kovalenko A. Opti.mized packings in space engineering applications: part II. Springer optimization and its applications. *Cham: Springer International Publishing*. 2019, pp. 439–457. DOI: 10.1007/978-3-030-10501-3_16 (accessed 28.08.2025)
106. Yakovlev S. Configuration spaces of geometric objects with their applications in packing, layout and covering problems. Advances in intelligent systems and computing. *Cham: Springer International Publishing*. 2019, pp. 122–132. DOI: 10.1007/978-3-030-26474-1_9 (accessed 28.08.2025)

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ПРАКТИКО-ТЕОРЕТИЧНІ АСПЕКТИ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ ОПТИМІЗАЦІЙНОГО ПРОЦЕСУ УПРАВЛІННЯ МУЛЬТИГРУПОВОЮ ПОВЕДІНКОЮ АГЕНТІВ РОЗПОДІЛЕНИХ СИСТЕМ НА ОСНОВІ АЛГОРИТМУ ЗГРАЇ СІРИХ ВОВКІВ (GWO).

Дана робота зосереджена на прикладних аспектах та особливостях роботи алгоритму зграї сірих вовків (GWO) в контексті застосування в мультиагентних розподілених системах. У цій статті представлені наукові матеріали щодо запропонованих власних ідей, припущень та гіпотез для аналізу та подальшої перевірки в галузях комп’ютерних наук, методів оптимізації та розв’язання прикладних математичних та інженерних задач. **Об’єкт дослідження –** процес організації розподілених систем на основі обчислювального інтелекту. **Предмет дослідження** – організація алгоритмічної взаємодії у мультиагентних інтелектуальних системах в контексті математичного моделювання оптимізаційного процесу управління мультигруповою поведінкою. **Мета роботи** – дослідити ключові практико-теоретичні прикладні аспекти та специфіку застосування алгоритму ройового інтелекту зграї сірих вовків (GWO) і його окремих алгоритмічних модифікацій, вивчити особливості моделювання поведінки інтелектуальних агентів зграї сірих вовків під керівництвом обчислювального інтелекту. Використані **методи:** метод аналізу та синтезу, абстракції та конкретизації, порівняння та аналогій, метод математичного моделювання та метод науково-пошукового експерименту. **Отримані результати:** 1) проаналізовано ґрунтовні теоретичні матеріали в області прикладного застосування алгоритму зграї сірих вовків (GWO); 2) проаналізовано ключові тактико-стратегічні прийоми математичного моделювання поведінки інтелектуальних агентів; 3) сформовано загальні підходи математичного моделювання мультигрупової взаємодії самоорганізованих мультиагентних формувань; 4) розглянуто та проаналізовано проблематику координації та агентної взаємодії у мультиагентній розподіленій системі; 5) розглянуто прикладне застосування мультиагентних систем в задачах науки, інжинірингу, комп’ютерних та роботизованих систем; 6) виявлено основні обмеження застосування алгоритму зграї сірих вовків. **Отримала подальший розвиток** концепція математичного моделювання алгоритму зграї сірих вовків (GWO) на прикладі окремо виділених тактико-стратегічних прийомів організації вовчої зграї у вигляді мультигрупової мультиагентної розподіленої системи. **Наукова новизна:** запропоновано новий спосіб вирішення вже вирішених вибраних задач оптимізації (окремі задачі оптимального пакування сферичних об’єктів в обмежений контейнер), які ми перерахували в статті. Основна ідея роботи полягає в підвищенні ітераційної швидкості та точності процесу алгоритму пошуку шляхом використання евристичного алгоритму ройового інтелекту, відомого під індексом алгоритму зграї сірих вовків (GWO). Нами запропоновано застосування спеціального якісно-числового показника для визначення ефективності роботи окремих агентів вовчої зграї за допомогою оціночних параметрів в процесі оптимізації або в реальному часі. Виявлено нові тактико-стратегічні прийоми організації вовчих зграй в процесі самоорганізації. **Практичне значення:** 1) нами висувається ідея-гіпотеза, для перевірки в наступних роботах, котра ґрунтується на мультигруповій мультиагентній самоорганізації розподіленої системи на основі якісно-числових показників, котрі планується розраховувати виходячи із складних координаційно-характеристичних методів та евристичних динамічно-змінюваних даних. Пропонується перевірити гіпотезу про нові розрахункові оціночні параметри ефективності агентів вовчої зграї; 2) плануються майбутні роботи-дослідження задля розширення області застосування алгоритму зграї сірих вовків (GWO) у комбінації з перспективними іншими нашими ідеями в області обчислювального інтелекту задля вирішення вже відомих, але неефективно розв’язаних оптимізаційних задач; 3) в контексті процесу математичного моделювання з використанням алгоритму GWO, планується звернути увагу на проблему неприродності принципу генерації та розподілення випадкової величини у стохастичних змінних алгоритму, проблематику питання якого було недостатньо висвітлено у роботах, знайдених за посиланнями або може бути модифіковано задля підвищення ефективності роботи алгоритму у вирішенні обраних задач; 4) запропоновано, як нове рішення використання алгоритму GWO у вибраних задачах оптимального пакування сферичних об’єктів для їх більш ефективного вирішення. **Висновки** В даній роботі було розглянуто основні практико-теоретичні аспекти та багатогранність специфіки застосування оптимізаційного алгоритму зграї сірих вовків (GWO). Розглянуто прикладне застосування даного алгоритму у різних науково-практичних задачах в контексті математичного моделювання мультигрупової мультиагентної поведінки. Було проаналізовано базові принципи організації вовчої зграї, визначено окремі стратегії координації та полювання вовчою зграєю, було виявлено ключові характеристики та проблематику алгоритму зграї сірих вовків (GWO).

Ключові слова: обчислювальний інтелект; методи оптимізації; дослідження операцій; розподілені системи; оптимізатор зграї сірих вовків (GWO); ройовий інтелект; математичне моделювання; мультиагентні системи; оптимальна упаковка.

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