Optimization of medical logistics with bee colony algorithms in emergency, military conflict and post-war remediation settings*

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Abstract

The article discusses the application of bio-inspired Bee Colony Algorithm (ABC) in medical logistics, which is an important and promising direction in the conditions of the increasing scale and complexity of various risks and threats. The algorithm's ability to effectively adapt to changes, optimize resource use, and provide decentralized management makes it an essential tool for solving emergency medical care problem, mitigating military conflicts and natural disasters. The ABC can be effectively integrated with modern information technologies, such as Internet of Things (IoT) monitoring systems and autonomous drones, significantly multiplying their combined use. These technologies enable real-time data collection on the data on the state of damaged infrastructure, the nature and extent of damage, an analysis of medical resources requirements, and the optimal delivery of medical care. Combined with the ABC algorithm, such integration can significantly improve the efficiency and effectiveness of management decisions made in extreme complexity and uncertainty conditions. In modern realities, where traditional methods cannot cope with the dynamics and scale of the above-described problems, bio-inspired algorithms are an effective tool for increasing the flexibility and adaptability of the healthcare system, which can be used in international practice. The authors analyzed the feasibility of implementing the ABC to solve the logistical challenges of providing emergency medical care in military conflict zones and during emergencies. They prioritized the prompt delivery of medical resources such as medications, equipment, and medical personnel to areas needing assistance. The article thoroughly examines the practical aspects of using an integrated optimization algorithm, based on examples of recent military conflicts and natural disasters in conditions where delivery routes and needs for medical care can change quickly, and the number of available resources can vary.

The authors are focused on analyzing the advantages of the proposed integrated optimization algorithm for emergency medical logistics. They revealed that traditional planning approaches cannot adapt quickly to changes in resource delivery parameters. This study is comprehensive and encompasses a wide range of tasks. It includes organizing emergency medical care logistics during emergencies and military conflicts, as well as implementing post-war remediation tasks using the ABC approach in conjunction with modern IT solutions and IoT.

Keywords

Bee Colony Algorithm (ABC), Internet of Things (IoT), IT solutions, emergency medical logistics, emergency medical care, remediation.

1. Introduction

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In recent years, the world has been facing an increasing number of crises, such as military conflicts, natural disasters and environmental catastrophes, which require healthcare systems to provide effective and prompt solutions to provide medical care. These threats are characterized by a high degree of complexity, unpredictability and scale, which requires fundamentally new solutions in the medical field, especially at the emergency response stage when such a situation occurs, and then at the stage of remediation from its consequences. Advanced information technologies, particularly bio-inspired optimization algorithms like the artificial bee colony (ABC) algorithm, integrated with advanced IT technologies, play a crucial role in managing complex systems such as emergency medical logistics. These algorithms excel at solving optimization problems in conditions involving multitasking and high uncertainty. The ABCs can effectively optimize delivery routes and resource allocation based on real data obtained using IoT devices and monitoring systems. This is critical, for example, in conditions of destroyed infrastructure, a prompt search for alternative routes for essential resource delivery can save numerous lives.

Using bio-inspired technologies not only in emergencies but also in military activities, as well as in post-war remediation. Our in-depth study of this range of issues was also inspired by the publication of Javad Behnamyan and Zikha Kiani Untirta [2] in the context of expanding the scope of application of fairly new, but already proven biotechnologies, such as ABC. In addition, the research work of Jinbao et al. (2023) served as the basis of our ideas concerning optimizing emergency medical logistics.

The research is centered around the different metaheuristic algorithms to optimize emergency logistics. The main focus is on algorithms that can find solutions for problems with multiple constraints, which are essential for effectively managing medical logistics during crises.

These ideas became the key focus of our research into the feasibility of applying bio-inspired technologies not only in emergency situations but also in military operations and post-war remediation. Our in-depth study of these issues was also inspired by the publication of Javad Behnamian and Zikha Kiani Untirta [2], which explored the expansion of relatively new but already proven biotechnologies, such as ABC (Artificial Bee Colony). Furthermore, the research by Jinbao L. et al. (2023) played a significant role in substantiating our ideas in the context of optimizing emergency medical logistics. Their work focuses on using various metaheuristic algorithms to optimize logistics in unforeseen circumstances, particularly emphasizing algorithms that solve multi-constraint problems crucial for effective medical logistics in crisis scenarios.

Considering all factors affecting emergency medical logistics is fundamentally important. Thus, a study by Chinese scientists indicates the need to consider the multi-cyclical nature of the supply of emergency medical resources in uncertain conditions with limited transportation capabilities. [4]. Research on multi-purpose supply management of relief supplies led us to believe that our study would be highly relevant and significant in the recovery efforts in active military areas affected by various weapons [5]. To study the management aspects of optimizing emergency medical logistics, we analyzed the study of a bio-objective model for planning logistics services in emergencies based on uncertain conditions [6].

Effective emergency medical care management process largely depends on the rational distribution of specific medical supplies. We adopted and applied the principles of the distribution of essential supplies during the COVID-19 pandemic based on cloud computing, described by [7]. Bingqing Zhang's article is devoted to studying the various aspects of optimizing the emergency logistics network based on a cloud platform, which expanded our understanding of the possibilities of integrating the ABC optimization algorithm with advanced computer technologies [8]. We explored the potential use of drones and data satellites to optimize delivery routes and minimize risks in medical logistics. We concluded that their integration into the ABC optimization model can greatly reduce the speed of delivering the necessary resources to the places of their urgent need. The idea was inspired by a team of researchers focusing on developing an algorithm to optimize an adaptive ant colony for real-time logistics functions in emergency delivery.[9].

Crisis logistics largely depend on weather conditions. Our study applied the adapted ideas of Bogdanova L. on emergency logistics management in crisis weather conditions [10]. The author's scientific views are completely consistent with our position that the success of logistics operations depends, first of all, on making informed decisions that should take into account various factors, including weather conditions, the nature of the crisis, its causes, the number of affected people, the nature of injuries, etc. Particular attention is focused on the role and importance of IT systems in database updating. The analyzed above publications highlight the significance of effectively managing medical logistics during extreme situations. They stress the need for comprehensive management of this process, specifically emphasizing the importance of preparedness to minimize losses and save human lives.

2. Materials and methods

The topic of this study is transdisciplinary and includes intersections with several disciplines: public health and healthcare, healthcare economics, logistics and supply chain management, algorithmic optimization, big data and the IoT, bioinformatics, and machine learning. In this context, the key methodological approaches that form the "core" and the set of first-order scientific methods of our transdisciplinary research are the optimization ABC – the core of the model, and together with it – the systemic, complex, synergetic, adaptive, situational approaches, optimization modelling. Each methodological approach plays a unique role, complementing others to ensure the integrity and depth of scientific analysis.

The ABC is bio-inspired and focused on the bee behavior principles methodological solution, providing a core of innovative model adapting to environmental changes, enabling quick resource redirection and plan adjustments. Artificial Bee Colony Optimization is a polynomial heuristic algorithm widely used to solve optimization problems in computer science and operations research. This algorithm is a stochastic bionic algorithm based on simulating the behavior of a honeybee colony when collecting nectar in nature. It was developed and proposed for use by D. Karaboga in 2005. Over the past nearly twenty years, numerous teams of scientists in various countries have researched the behavior of bee colonies to address problems more effectively, using this algorithm. The study of the interaction of bees with the environment and within the swarm suggested approaches to finding optimal solutions Studying the interactions of bees with the environment and within the hive has suggested approaches to finding optimal solutions in a large, complex and multi-level society like ours. Scientists began to model "swarm intelligence" - attempts to make robotic, automatic and automated swarms.

A single bee is just an insect with a brain barely larger than a pinhead, a colony of bees is capable of solving complex optimization problems through the coordinated actions of a large number of its inhabitants. Bees successfully search for and find new sources of food and building materials for the hive and accurately transmit information to their fellow bees, who, in turn, can quickly, "on the fly", update their knowledge of the location of flowers and optimally rebuild flight routes over and over again, saving time and energy.

The bee colony algorithm includes initial exploration and subsequent work of the bees of the hive. During initialization (initial exploration), exploration of the space features is performed to determine, Kn, the most promising points with the best values of the objective function $f(X)=f(x_1,x_2,..., x_{nn})$, which are stored in the hive. After this, local reconnaissance is conducted near the chosen points within a specified reconnaissance radius R to refine the solution and improve the result. When an improvement is made, the updated value of the result (f) and the corresponding set of parameters for the objective function (X) are saved in the hive. By combining the work of scout bees and worker bees over a given number of iterations C, the algorithm ensures a gradual improvement of the remembered sample $R = [X_1, X_2,...,X_K]$ from K solutions. Upon completion of its work, the best solution is selected from the specified set of solutions, which is the result of the algorithm [11], [13], [14], [15], [16], [17], [18], [19].

A graphical representation of the ABC optimization algorithm in 2D is shown in Figure1.

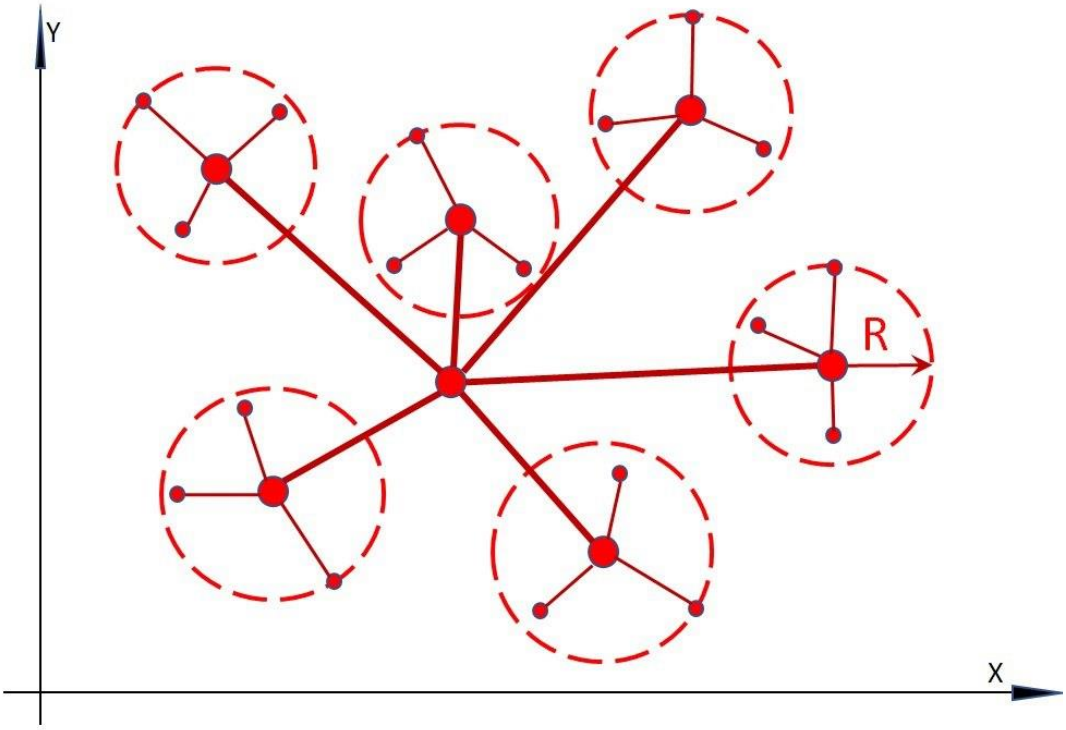

Figure 1: Image of the strategy of the reconnaissance algorithm in a bee colony, 2d space*
* Note: the bold lines in the figure indicate the flights of scouts, and the thin lines indicate the refinement of decisions by worker bees)

We fully agree with the position of the team of authors who conducted comparative analyses of the modified ABC and other bio-inspired methods that "... the bee colony model is simple, has few parameters and is very universal, which easily falls into the local optimum" [12]. In principle, the properties of this approach (logical and quite understandable) focused our attention on its applicability aspect in finding solutions to this type of research problem (Table 1).

Table 1
Advantages of using the ABC optimization algorithm to solve the problems of emergency medical care logistics in military conflict zones or emergencies

Problem	ABC application
1. Optimization of routes and resources:	
In an emergency or military conflict, rapid delivery of medical supplies, equipment and personnel is required, and this is under highly changing conditions (destroyed infrastructure, weather conditions, hazardous areas, changing priorities).	The ABC algorithm can effectively find optimal routes based on the identified key factors and ways to distribute medical resources by adjusting to them. This is especially useful for planning routes for medical teams, evacuating the wounded, or delivering medicine in difficult conditions and damaged infrastructure.
2. Scalability and adaptability	
Emergency medical logistics require high flexibility and rapid adaptation to new information and updated data (changing weather, moving active combat operations or increasing threats of new natural disasters).	The bee colony algorithm can easily adapt to real-time changes in these and other conditions. For example, if a medical supply route becomes inaccessible due to a fire or mass fire attack, ABC can quickly analyze alternative delivery routes, minimizing delays in assisting.
3. Decentralized management:	

In the absence of centralized control (for example, in areas with a destroyed communication and communications system), decentralized adoption of operational management decisions is required to successfully coordinate actions to deliver medical supplies.	The bee swarm algorithm is based on decentralized problem solving, which allows each "agent unit" to independently make operational management decisions based on the aggregated information received, including from "scout bees" - drones.
4. Inventory and resource management:	
In conditions of limited resources (blood for transfusion, specific medications, equipment), and in some cases their absence, effective distribution and management of stocks is required.	The ABC is applicable and can help optimize the allocation of resources across emergency medical care centers based on current needs, task priorities, and available resources.
5. Integration with drones and robotic systems:	
Modern logistics actively uses progressive technologies: unmanned technologies (driverless cars, robotized equipment, various types of drones) to deliver medicines, especially to hard-to-reach places.	The bee colony algorithm is successfully integrated with unmanned and robotic equipment to optimize the routes for the delivery of medical supplies, as well as to coordinate autonomous equipment involved in the evacuation
6. Scenario analysis and strategic planning:	
In emergency medical logistics, it is necessary to consider several alternative scenarios for the situation development (from the rapid movement of the front to the emergence of new emergencies).	The ABC algorithm allows the simulation of various scenarios and planning strategies depending on the availability of vehicles and equipment, the request for a certain amount of medical supplies and their actual availability, and depending on the development of an emergency.

The use of artificial intelligence (AI) in the optimization modelling of emergency medical logistics will significantly increase the efficiency of decision-making in conditions of uncertainty and multitasking, which is extremely important for medical logistics in emergencies, such as earthquakes, floods, fires, as well as in the localization of military conflicts. This approach will occupy one of the key places in the "core" of the methodological model, since right AI allows realization of the full potential of other methodological approaches, such as adaptability and self-organization.

The systems approach allows us to consider medical logistics as a complex dynamic system that consists of many interconnected elements: the transport and logistics system, the medical care system, medical resources, infrastructure support, management system, etc. This is important for understanding how the various components of the system and incoming subsystems interact with each other in an emergency.

The integrated approach focuses on the whole problem, considering all its aspects and multi-level interactions. In the case of applying ABC in emergency medical logistics, it is necessary to consider not only the physical delivery of resources, but also factors such as the speed of response to crisis events, the availability of communications, the state of the infrastructure, and the dynamics of changing situations. An integrated approach will allow us to create models considering the crisis's multifactorial and multi-level nature.

The synergetic approach involves studying complex systems, specifically the effect of increasing system efficiency through its component's integration and merging into a unified whole due to emergence. Concerning medical logistics, especially during emergencies, it is vital to ensure that the system's each element can independently execute its functions and interact effectively to achieve a common goal. However, the effect of joint coordinated interaction will only be enhanced by integration. The adaptive approach is focused on the ability of the system to quickly and effectively change its structure and functional qualities in response to changes in internal and external environmental factors. In conditions of military conflicts or natural disasters, the adaptability of the logistics system is vital for providing medical care. This directly correlates with the essence of the ABC algorithm, since it is adaptive in itself - it allows you to "rebuild" on the go, changing routes and resource distribution in response to changes at a certain point in time, taking into account several factors such as weather conditions, traffic conditions, infrastructure conditions, etc. Using an adaptive approach in the study will allow us to model situations in which emergency medical logistics must immediately respond to changes and offer optimal solutions. A bio-inspired ABC algorithm, with integrated real-time monitoring systems (e.g., use drones and satellite systems), will allow us to quickly respond to changing conditions and direct resources where they are most needed.

The situational approach involves the analysis of specific conditions and circumstances in which the system operates. In the context of medical logistics in emergency situations and military conflicts, this approach emphasizes the uniqueness of each crisis situation. Each such situation requires an individual approach, and it is important that the algorithms can effectively adapt to the specific conditions of the situation, characteristic of a particular region, crisis, or availability of specific resources. This will allow the ABC algorithm to best solve specific logistics problems.

A cybernetic approach to control and modeling systems can be useful for analyzing feedback in the medical logistics system, which is important for its adaptability and adjustment of actions based on changes in the environment.

Heuristic research methods allow finding optimal solutions to problems under conditions of limited information and time. In the context of crisis medical logistics, this is extremely important, since it is impossible to always have complete information about the situation.

We also believe that it is appropriate that the inclusion of dynamic modeling and agent-based modeling (ABM) in the methodological model will be useful and justified. These approaches will provide a more in-depth analysis of complex interactions and help model the behavior of the system in changing conditions. They thus expand and complement other approaches, offering more precise and comprehensive solutions for optimizing medical logistics in emergency situations and post-war remediation.

In Figure 2, we present an integrative methodological design of a set of methods that will be applicable together with the ABC optimization algorithm in the organization and management of emergency medical logistics, namely: a set and organic integration of first-order scientific methodological approaches (around the “core” - author's note) and the “periphery” - a set of auxiliary, complementary and specific research methods.

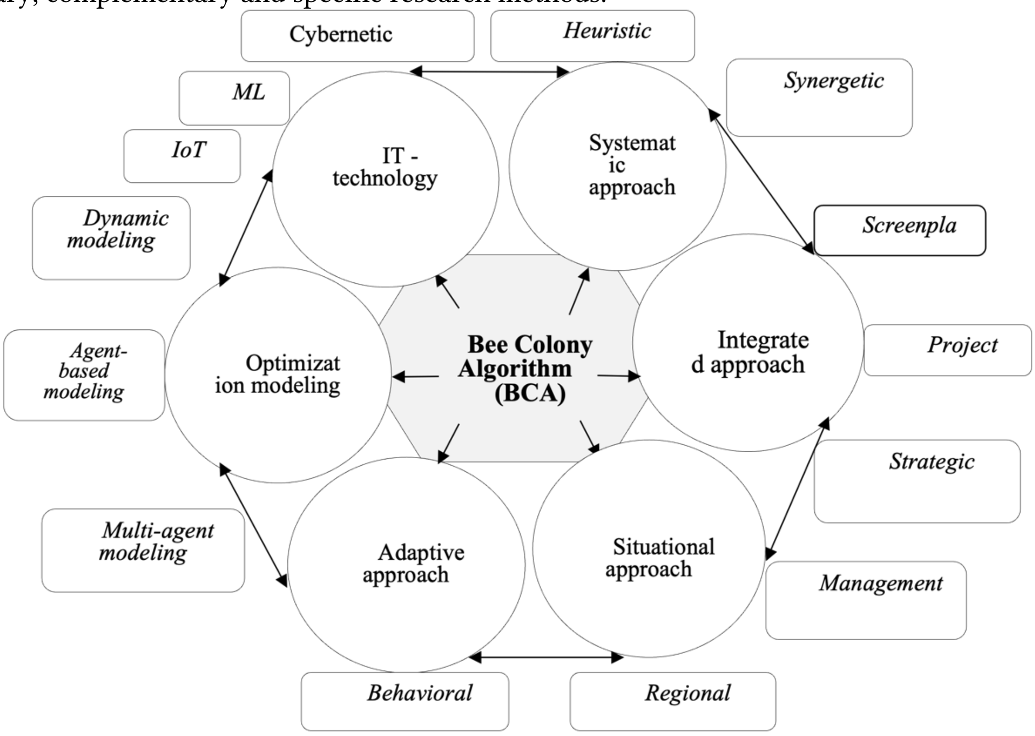

Figure 2: Structure of the methodological design for the application of the bee colony algorithm (ABC) in emergency medical logistics

Based on a comprehensive analysis of scientific approaches that are most often used by researchers in solving problems of emergency medical logistics management, we came to the conclusion that it is advisable to identify a productive combination consisting of 7 scientific approaches that form the core of the methodological model, the center of which is the bee colony algorithm and 14 auxiliary scientific approaches that can be selected to solve specific problems.

3. Empirical model based on ABC and its integration References

To develop an optimization algorithm for ABC taking into account the possibilities of integrating it with advanced IT technologies, AI, IoT, and ML, we studied the proposals of other scientists who studied real crises and the experience of emergency medical logistics in military activities, namely:

- COVID-19, the ABC algorithm was used in China for the dynamic distribution of medical resources (medicines, equipment) in a crisis, which improved the speed and accuracy of delivery of materials to the necessary medical institutions. This experience can serve as a positive example of the application of ABC in medical logistics in any crisis [21];
- The earthquakes in Turkey and Syria that occurred on February 6, 2023, killed more than 53,500 people in Turkey and from 5,951 to 8,476 people in Syria. The casualty toll is also high, with more than 107,000 casualties reported in Turkey and around 14,500 injured in Syria. The earthquake was one of the most devastating in the region's history, causing widespread destruction in cities such as Gaziantep and Aleppo. We have thoroughly studied the published research related to the analytical scientific analysis of this emergency event, but they did not cover the issues of organizing logistics. At the same time, the authors' ideas on using social networks (WhatsApp, Twitter) for transmitting data from victims to rescuers at their location, and technological integration with hotline chatbots can be useful in solving the issues we are studying and were taken into account. Special consideration should be given to the documented and analyzed experiences presented in the article. This is crucial when preparing for emergencies and handling real-time data from IoT devices, like drones. Social networks can also improve emergency logistics coordination [22]. Furthermore, the proposed scientists' concept regarding the rational distribution of food can be implemented in the developed by us model [23].
- Additionally, the military actions in Ukraine, specifically the missile strike on the Okhmatdet Children's Hospital in Kyiv on July 8, 2024, should be noted. More than 50 people were injured, including seven children. The strike destroyed one hospital building and damaged four others. The missile strike on Okhmatdet, the largest children's hospital in Ukraine, was part of a larger attack in which Russian forces launched more than 40 missiles at cities in Ukraine. The strike injured children undergoing treatment, including those undergoing dialysis at the hospital. This attack caused international outrage and discussions about the possibility of prosecution for war crimes. However, the authors of this article did not cover this event in the framework of optimizing emergency logistics in cities, which also has its specifics. In the next stage, the designed structure (presented in Figure 3) of the interaction of key subjects managing the first medical aid and emergency logistics will be analyzed.

We have identified the key entities involved in managing such emergencies to identify the specifics of their interaction. The model we are developing includes:

1. Central Coordination Headquarters (CCH):

- role: Managing all operations, planning, interacting with government and international organizations;

- interaction with other entities: receiving current data from all units (medical teams, logistics departments) to make optimal management decisions on delivery priorities and resource allocation.

2. Medical Resources Logistics Unit (MRLU):

- role: ensuring and monitoring the receipt and distribution of medical resources;
- interaction with other entities: following direct instructions from the CCH and directly interacting with medical teams to deliver medications and equipment to affected locations.

3. Rapid Response Medical Brigades (RRMB):

- role: Providing emergency medical care and preparing for evacuation from emergency areas;
- interacting with other entities: Transferring data to the Central Command Center about the situation on the ground to coordinate further actions and deliver the necessary resources.

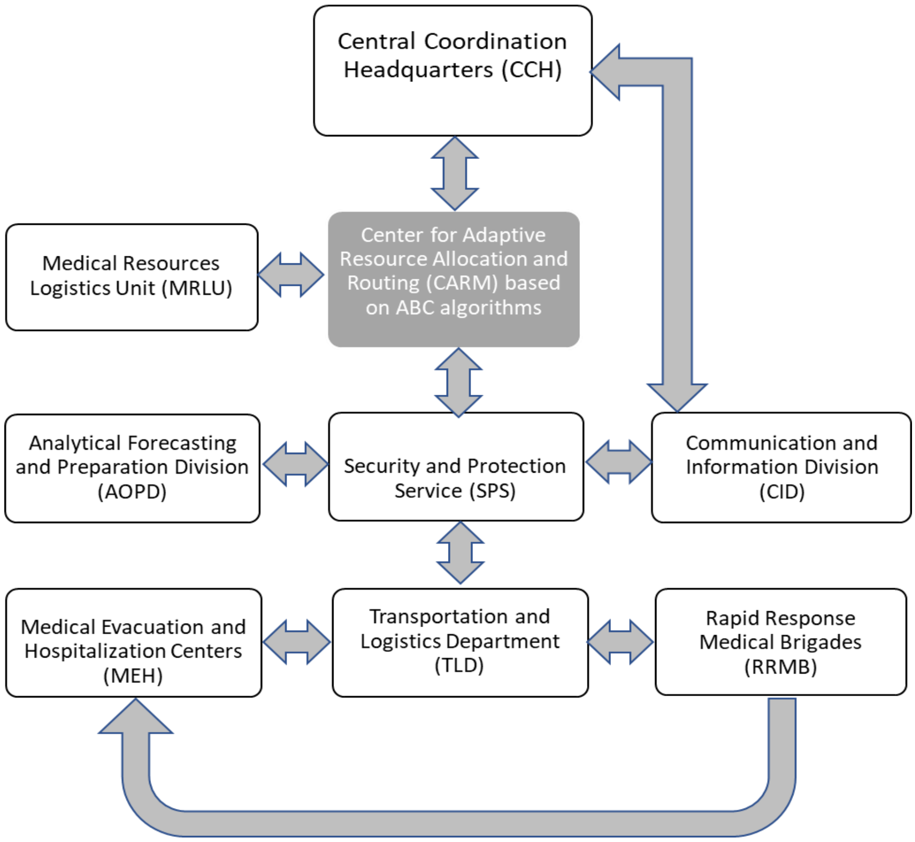

Figure 3: Structure and interaction scheme of key subjects of the management of the process of providing first medical aid based on ABC

4. Transportation and Logistics Department (TLD):

- role: planning and coordinating all modes of transport (aircraft, land, water) for medical resources delivery and evacuation of victims. Managing logistics warehouses and warehousing to ensure continuous supply of necessary resources. Optimizing routes and minimizing delivery times given the current situation. Monitoring the transportation safety and the security of medical supplies in high-risk areas.
- interacting with other entities: works closely with the Central Coordination Headquarters (CCH) to gather data on priority medical resource delivery. Liaise with the Center for Adaptive Resource Allocation and Routing (CARM), which adjusts delivery routes based on real-time data considering the damage or blockages. Ensures prompt exchange of

information with the Communications and Information Center (CIC) to transmit timely data on the availability of resources, the state of infrastructure support and route changes.

5. Communications and Information Division (CID):

- role: ensures communication between all participants;
- interaction with other entities: coordinates data collection, processing and transmission between the military, civilian structures and international organizations involved in emergency assistance.

6. Medical Evacuation and Hospitalization Centers (MEH):

- role: Assess the condition of victims and organize their movement;
- interaction with other entities: direct interaction with MEH to address the implementation of emergency evacuation and placement of victims.

7. Analytical Forecasting and Preparation Division (AOPD):

- role: In-depth risk analysis and development of long-term strategies.
- interaction with other entities: transfers the results of analysis and assessment of alternative scenarios to MEH for strategic planning and provision of resources.

8. Security and Protection Service (SPS):

- role: Ensuring personnel safety and medical resources safety.
- interaction with other entities: Interacts directly with the CCS and the Transport and Logistics Department (including warehouse entities – author's note) to ensure safety in all areas of emergency medical care and logistics;

9. Center for Adaptive Resource Allocation and Routing (CARM):

- role: select optimal delivery routes and optimal resource provision in real-time with the use of ABC.
- interaction with other entities: Processes data received from drones, satellites and response teams, as well as first aid teams on the ground, interacts directly with the CCS to coordinate the operational management process, primarily the most efficient provision of medical resource delivery services to emergency locations.

The next step in the development of the model will be visualization of the ABC algorithm in 3D format (Figure 4).

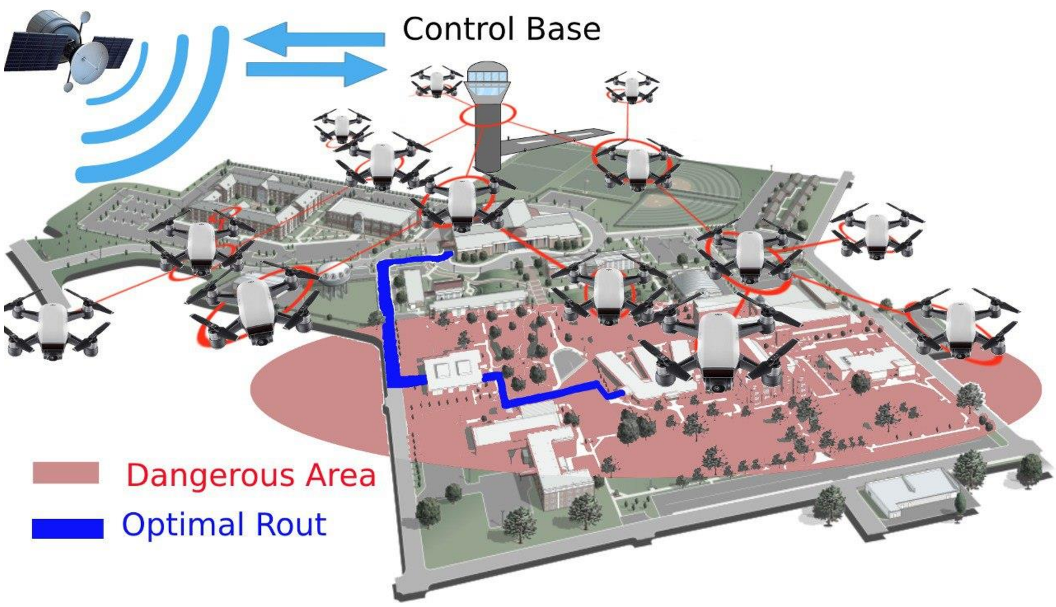

Figure 4: 3D image of the algorithm for reconnaissance and transmission, data processing to optimize emergency medical logistics routes based on ABC

Based on the above, an integrated model for optimizing emergency medical logistics routes based on ABC of a bee colony with the integration of IoT, ML and other IT technologies, including the ability to take into account changes in weather conditions and destroyed infrastructure will look like this:

$$\varpi_{ij}(t) = \varpi^0_{ij} \cdot f_{wether}(t) \cdot f_{destructions}(t) \cdot f_{IoT}(t) \cdot (1+(Pml(t+\Delta t))/K) \quad (1)$$

where:

$\varpi_{ij}(t)$ — is the current weight of the medical resource delivery route *i→j* at time

ϖ^0_{ij} — is the initial weight of the delivery route (distance and travel time),

$f_{wether}(t)$ — is a coefficient that adjusts the overall route weight depending on changes in weather conditions (e.g. worsening weather increases the route weight),

$f_{destructions}(t)$ —is a coefficient that takes into account changes in the state of point and linear infrastructure (e.g. destruction of roads, hospitals, traffic jams),

$f_{IoT}(t)$ — is a coefficient based on data transmitted from IoT sensors that make adjustments by updating current data on changes in the situation (e.g. sensors record and transmit parameters of weather conditions, current state of roads, traffic jams, etc.),

$P_{ml}(t+\Delta t)$ — a forecast calculated using ML allows predicting the state of routes after Δt time, taking into account weather changes (improvement or deterioration) and infrastructure changes (restoration or destruction/failure),

K — is the normalization coefficient that determines the degree of influence on forecasts generated by ML of a set of alternative routes for medical resources delivery.

For a detailed content analysis of the presented integrated ABC model for optimizing routes for emergency medical logistics, we present a description of its key elements:

ϖ^0_{ij} — the base weight of the route, which reflects the initial conditions (e.g., normal delivery time, the distance between points of the logistics route). This is a static value before the algorithm starts to consider the impact of external factors.

$f_{wether}(t)$ — a function of weather conditions that changes route weight depending on current and forecasted weather changes. For example, if heavy rain or snowfall starts, the weight increases so that the "bees" choose more optimal and safe delivery routes,

$f_{destructions}(t)$ — is a function that reflects the state of the infrastructure at a certain point in time. If data transmitted from drones or sensors reports the destruction of railway tracks or a bridge, the route weight increases sharply or becomes infinite, which makes the route unsuitable for choosing emergency delivery of medical supplies,

$f_{IoT}(t)$ — is a coefficient depending on the data collected from the IoT- sensors at a given point in time. These sensors can provide information about traffic, road conditions or other specific obstacles that influence the choice of the optimal delivery route,

$P_{ml}(t+\Delta t)$ — is the forecast calculated by ML about the availability of the restored delivery route after a certain time. This can be useful for predicting how the availability of alternative routes for medical resource logistics will change in the future (for example, if active restoration work is underway on railway lines or weather conditions are predicted to improve).

K — is a normalizing coefficient that determines how much the ML forecasts will influence route selection compared to current conditions.

This formula combines the model's all the components, allowing the bee colony algorithm to dynamically adapt to the changes in infrastructure, and weather conditions and use modern IT technologies to make optimal decisions in emergency medical logistics.

The main stages of the proposed ABC model:

1. Data collection from IoT and drones: sensor systems collect information about the state of the infrastructure and weather conditions; drones and sensors transmit data on destruction and other obstacles.
2. Real-time data processing: ML analyzes the collected data and makes forecasts about the future state of delivery routes (e.g. restoration of a highway or worsening weather conditions).
3. Decision making by the integrated ABC algorithm: "scout bees" explore possible routes for the delivery of resources, "forager bees" perform the assigned real logistics tasks, and

"observer bees" analyze all possible delivery routes and choose the most effective routes based on the collected data.

4. Optimization of emergency logistics routes in real time based on changing conditions: continuous data update and formation of optimal logistics routes in real-time; the system allows dynamic adaptation to changes in infrastructure and weather conditions, thus changing the route weight based on the information received.
5. Reporting and adjustments: ML models adjust routes by learning from new data received to optimize the system's operation in the future.

Implementation example:

If, for example, the road $i \rightarrow j$ was accessible (low weight), but was hit by heavy snowfall and a drone reported the destruction of a part of the road, the coefficients $f_{weather}(t)$ and $f_{destruction}(t)$ will sharply increase the route weight, which will force the "scout bees" to look for alternative routes for emergency delivery of medical supplies.

At the same time, the ML model can predict that the road will be cleared in 6 hours, which will be reflected in the coefficient $P_{ml}(t+\Delta t)$ and the system will allow choosing this route for future use when weather conditions improve.

The practical application of the integrated model for optimizing emergency medical logistics routes based on the Bee Colony (ABC) algorithm, using IoT technologies, machine learning (ML) and other IT technologies, is critical for effective management in emergencies. This model allows for the dynamic adaptation of routes in real time, taking into account possible changes in weather conditions and the destruction of linear and point infrastructure, which is especially important for disasters such as earthquakes, fires or military conflicts.

Detailed significance of using the integrated ABC optimization model:

1. Operational adaptation of routes. ABC-based control systems can instantly respond to changes in critical situations, transmitted via IoT sensors or drone data, allowing for updates and optimal routes for the delivery of medical resources. This is especially important in the context of natural disasters, such as the earthquakes in Turkey and Syria, where the destruction of infrastructure requires constant monitoring and adjustment of logistics.

Forecasting and predictive analytics. Using ML machine learning allows for the most accurate forecasting of future changes, such as the restoration of roads for the delivery of goods and medical personnel, as well as worsening weather conditions. This allows for pre-adjustment of routes taking this into account, which increases the efficiency of emergency medical logistics and reduces delays in assisting in disaster areas, as was the case with the massive fires in Australia and the USA.

3. Saving lives in wartime. In military operations, such as those currently taking place in Ukraine, the use of ABC and IT technologies helps to optimize routes for the evacuation of victims and the delivery of vital medical resources. Timely delivery of medical care in the shortest possible time can minimize civilian casualties and increase the resilience of medical logistics in the face of destruction of various types and scales. In the context of military activity, after the end of its active phase, the use of the integrated ABC model presented in the article will effectively solve a set of problems of medical care for the affected population as part of remediation. In conclusion, we have aggregated and presented a generalized description of the necessary software and hardware for the implementation of an integrated model for optimizing emergency medical logistics routes based on the Bee Colony (ABC) algorithm with the integration of IoT, machine learning (ML) and other IT technologies (Table 2).

Table 2
Hardware and software for implementing the ABC model

Element	Necessary software	Technical support
Bee Colony Algorithm (ABC)	- Python with libraries for optimization (e.g. DEAP, SciPy)	- High-performance servers for computing
Internet of Things (IoT)	- Node-RED for integrating and managing IoT devices	- IoT sensors transmitting parameters of conditions:

	- AWS IoT Core or Azure IoT Hub for processing sensor data	temperature, humidity, road conditions, monitoring of objects - Drones and mobile sensor devices
Machine learning (ML)	- TensorFlow, PyTorch for creating and training forecasting models scikit-learn for simple machine learning models	- Graphics processing units (GPUs) for accelerated data processing - Big data storage and processing systems
Real-time data analysis	- Apache Kafka or Apache Flink for stream data processing - MATLAB or R for data analytics and visualization	- Servers for real-time data analysis - Network data storage
Geographic data and mapping of logistics delivery routes	- ArcGIS, QGIS for working with cartographic data Google Maps API for Dynamic Routing	- Satellite images and GIS services - GPS trackers on vehicles
Monitoring of point and linear infrastructure, as well as weather conditions	- OpenWeatherMap API for getting weather data NASA FIRMS for Fire Monitoring	- Video surveillance with drones - Automated weather stations
Communication systems	- Twilio API, Slack API for communication between departments	- Mobile and satellite phones for emergency communications
Security and data protection	- AWS Shield or Cloudflare for protection against DDoS attacks	- Secure cloud data storage
Visualization of logistics routes and data	- Tableau or Power BI for data visualization	- Monitoring displays and workstations
Logistics and transport management	- AnyLogic for modeling agent-based systems - MATLAB Simulink for simulating logistics processes	- Specialized vehicles with sensors and trackers - Transport hubs and warehouses for storing resources

4. Discussion and Future Directions

This study presented an integrated route optimization model for emergency medical logistics based on the ABC using IoT, machine learning, and other IT technologies. Further discussion is needed on how effectively the model adapts to dynamic changes in infrastructure and weather conditions, which is especially important in the context of natural disasters and military conflicts. In the future, we plan to focus on deeper integration of this model with blockchain technology to ensure the security and transparency of data transfer. This will improve coordination between various entities involved in emergency medical care management and strengthen the resilience of medical logistics in conditions of high uncertainty and risk.

5. Conclusions

An integrated model for optimizing emergency medical logistics routes based on the ABC algorithm using IoT, machine learning (ML) and other IT technologies allows for dynamic adaptation of medical resource delivery and casualty evacuation routes in real-time, considering weather conditions changes and infrastructure destruction. This significantly improves the efficiency and safety of logistics, especially in natural disasters such as earthquakes in Turkey and Syria, fires in Australia and the United States, and military conflicts in Ukraine. Such a system can significantly reduce the number of casualties by providing timely medical care in critical situations.

6. Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT to: partially translate the original text from Ukrainian into English and check grammar and spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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