Architecture-oriented agent-based model (AOAM) for optimizing transport evacuation management and emergency medical assistance in the context of the war in Ukraine: challenges and prospects*

Tetiana Cherniavska [1,*,†], Bohdan Cherniavskyi [1,†]

[1] *University of Applied Sciences in Konin, Przyjaźni 1, Konin, 62-510, Poland*

Abstract

The article addresses the pressing and significant issues of managing the process of transport evacuation for those affected by military actions, as well as managing emergency medical assistance for the wounded. Amidst the ongoing active warfare in Ukraine, there is a growing need to integrate the efforts of all stakeholders—on the one hand, those overseeing these operations at all levels of the hierarchy, and on the other hand, those directly executing them in the field where emergency aid is provided. According to the authors, effective management of these processes is feasible through a model that not only swiftly responds to constant changes but also facilitates efficient coordination among stakeholders. Such a model is the Architecture-Oriented Agent-Based Model (AOAM), which meets all the requirements of crisis management. The research includes a parametric analysis of existing models to identify the optimal one, considering a combination of factors, key characteristics, and limitations. The authors also explore the challenges of developing and implementing AOAM, given the scarcity of financial and technical resources, and propose alternative approaches for project execution. The article examines the potential for expanding the functionalities of the proposed AOAM through its integration with GIS technologies. Furthermore, the research investigates the prospective applications of this integrated model in remediation operations and its use in peacetime.

Keywords

Architecture-Oriented Agent-Based Model (AOAM), Geographic Information System (GIS), Crisis Management, Transport Evacuation, Emergency Medical Assistance, Remediation.

1. Introduction

It should be recognized that in the context of ongoing active military actions in Ukraine and the extensive destruction of its territory by various types of weaponry, the task of rapid response to such events has become urgent and significant. This includes the organization and management of the transport evacuation process, as well as the management of emergency medical assistance. Ultimately, the number of civilian lives saved and the survival of wounded soldiers evacuated from the battlefield depend on this. Swift and coordinated activity by management structures at all levels of hierarchy, along with prompt management of emergency medical care, requires a well-organized and effective organizational and administrative mechanism [1].

The purpose of this study is to conduct an objective analysis of existing models for managing transport evacuation and emergency medical assistance used in foreign countries, in order to select the most optimal management model for application in the context of Ukraine [2, 3]. The authors' focus is primarily on the possibilities and challenges associated with the development and implementation of the Architecture-Oriented Agent-Based Model (AOAM), which has proven to be a promising model that meets the demands for clear coordination of actions among entities during crisis response situations.

IDDM'24: 7th International Conference on Informatics & Data-Driven Medicine, November 14 - 16, 2024, Birmingham, UK

* Corresponding author.
† These authors contributed equally.
tetiana.cherniavska@konin.edu.pl (T. Cherniavska); bohdan.cherniavskyi@konin.edu.pl (B. Cherniavskyi).
0000-0002-4729-2157 (T. Cherniavska); 0000-0001-9174-6139 (B. Cherniavskyi).

The conceptual impetus for our in-depth research on the potential of the Architecture-Oriented Agent-Based Model (AOAM) was drawn from the article titled "Architecture-Oriented Agent-Based Simulations and Machine Learning Solution: The Case of Tsunami Emergency Analysis for Local Decision Makers" [10]. In this publication, the authors focus on developing an agent-based model that integrates elements of machine learning and architectural modeling to optimize the organizational management mechanism for providing aid during emergency situations. The authors described AOAM as an approach that helps local authorities effectively manage interconnected processes such as evacuation planning, coordination of information flows to various structures, and the formulation of emergency evacuation plans for the wounded. This includes the delivery of medical supplies while dynamically updating information on the number of affected individuals, the nature of their injuries, routes, the evolving conditions of roads, climate factors, and forecasts of their changes. In the context of the ongoing military conflict in Ukraine, AOAM can be applied similarly to optimize the management of evacuation processes for the injured and emergency medical assistance, bringing together all government structures responsible for these operations. Just like in the tsunami scenario, the model can account for the constantly changing situation in zones where emergency assistance is provided, the condition of critical infrastructure, the availability of safe transport and logistics routes, and forecasted evacuation scenarios amidst ever-changing circumstances. As it is well-known, effective crisis management begins with the organization of key processes, and this will be the primary focus of our research.

Modeling (AOAM) within an organizational management structure is highly feasible for several reasons: this model allows for structuring the interaction of multiple agents, integrating real-time data, adapting to changing circumstances, and scaling to different objectives and tasks within certain constraints. Moreover, if GIS (Geographic Information Systems) is integrated into the proposed AOAM, its functional capabilities can be significantly enhanced. This hypothesis is supported by positive international experiences with the functioning of similar complex management systems, such as: Joint All-Domain Command and Control (JADC2) in the U.S., which integrates data from various military domains to optimize decision-making. Home Front Command in Israel, which coordinates crisis management, population evacuation, and emergency medical services during military operations. NATO Crisis Response System (NCRS), which handles coordinated responses to crises involving multiple countries. Copernicus Emergency Management Service (EMS) in Europe, which focuses on crisis management, including natural disasters and emergency response. All of these benchmarks incorporate AOAM elements into their crisis management and decision-making structures.

Thus, the unique characteristics of this model, such as its architectural flexibility and, at the same time, its ability to optimally organize the coordination of interaction between emergency response management entities, can make it an indispensable management tool at all hierarchical levels in Ukraine’s current conditions, as well as in the future during peacetime.

2. Materials and methods

First of all, it is necessary to formulate the definition of the concept of "architecture-oriented agent-based modeling." Architecture-Oriented Agent-Based Modeling (AOAM) is an approach based on modeling complex dynamic systems as a set of interacting agents, where the emphasis is placed on the structure and organization of interactions between the agents. In this context, the term "architecture-oriented" refers to the fact that the modeling process focuses on the structural elements of the system and their architectural relationships, which helps to better understand how different elements (agents) interact in various crisis situations for the purpose of organizing effective process management. However, unlike other agent-based models, AOAM emphasizes the architecture of the system—that is, how individual agents are structurally connected, through which channels information and resources are exchanged. This includes the analysis of hierarchies, roles, interaction protocols, and the overall design of the management system, allowing for more precise reproduction of complex processes such as overall evacuation management and the coordination of emergency medical assistance from a central command center [9, 10, 11].

For a clearer understanding of the functional capabilities, we present an aggregated general characteristic of Architecture-Oriented Agent-Based Modeling (AOAM), which will be detailed in Table 1.

Table 1

Analytical Assessment of Key Characteristics of the Architecture-Oriented Agent-Based Model (AOAM)

Characteristic	Description
Operating principles of AOAM	*Modeling agent behavior:* Each agent in the system is equipped with a set of specific rules or algorithms. These rules can range from simple ones (e.g., following a simplified route) to more complex ones (e.g., making decisions based on the current condition of an infrastructure object). *Communication and interaction:* Agents within the system can establish communication with each other, which is crucial for coordinated interactions aimed at achieving the set goals. *Feedback and adaptation:* Based on the analysis and forecast of the situation, the system continuously receives feedback from the agents, which allows it to model and select alternative scenarios.
Components of the AOAM structure	*Agents:* Each designated agent is a management entity at a specific level of hierarchy, with its own goals and functional capabilities. *Architectural connections:* These ensure the exchange of information and the coordination of coherent actions between agents. *Environment:* This is the informational and territorial space in which the agents interact.
Distinctive Features of AOAM Compared to Other Models	1. *Structural vs. Behavioral Focus:* AOAM focuses on a complex hierarchical system of agent interactions, specifically how agents are organized and how they interact with one another. This is crucial in crisis situations that require strict coordination among key agents, such as government-level management entities. In traditional agent-based models, more emphasis is placed on the behavior of agents and their interactions with their surrounding environment. 2. *Clear Hierarchy vs. Autonomy:* In AOAM, agents are organized in a hierarchy where certain agents manage or coordinate the actions of lower-level agents (for example, government bodies managing the actions of medical and evacuation services in chemically contaminated zones). In standard agent-based modeling, agents typically operate autonomously, and role-based or hierarchical relationships are less pronounced. 3. *Systemic Management vs. Decentralization:* AOAM is often applied to systemic management, where the focus is not only on how individual agents act but also on how the entire system is governed. Other types of agent-based modeling usually focus on more decentralized processes, emphasizing interactions and reactions of agents within their environment, often without a clearly defined systemic organization. 4. *Template-Based vs. Variability:* AOAM uses architectural templates that help structure and clearly regulate agent interactions. In contrast, other models may allow for greater variability and flexibility in the way agents interact and respond to environmental changes. In classical agent-based modeling (ABM), the emphasis is primarily on the behavioral models of agents and the variability of their reactions to environmental stimuli.
Advantages of AOAM in Crisis Situations	*Improved Coordination:* The clear structural system in AOAM enables efficient coordination of agent actions, which is particularly crucial in crisis scenarios with limited resources and time constraints. This structured coordination

	ensures that various management entities at different levels of the hierarchy work together in a synchronized manner, avoiding bottlenecks and delays. *Flexibility and Adaptation:* AOAM's ability to quickly respond to changing conditions allows it to adapt to new situations efficiently. In crisis management, where conditions can shift rapidly, this flexibility is essential for ensuring that the system remains effective and responsive, adjusting strategies as needed based on real-time data. *Scenario Analysis:* AOAM facilitates the modeling of various crisis scenarios, allowing decision-makers to test multiple response strategies in advance.

In order to justify the optimal choice of the model and objectively analyze its future structure, we used the scientific method of comparativism. In a broad, commonly accepted sense, comparativism (from the Latin comparativus—comparative) refers to the comparative study of various objects or phenomena. It is used in different fields of knowledge, helping to identify commonalities and differences, reveal patterns, and develop universal approaches to problem-solving.

Thus, comparativism is a methodological approach based on a comparative study that allows for a deeper understanding of the phenomena being studied (in our case—the features, advantages, and disadvantages of the models). It also helps to identify their cause-and-effect relationships and common functioning patterns [4].

At the start of our research, we propose to analyze the positive international experience of using AOAM in various spheres of human activity (Table 2).

Table 2

Positive International Experience in the Implementation of AOAM

Country Implementing AOAM	AOAM application
1. Management of Energy System:	
USA	In the United States, AOAM was applied to assess the impact of Hurricane Sandy in 2012 on the energy infrastructure of New York City. This modeling helped predict potential power outages and implement measures to minimize their consequences.
2. Healthcare and Emergency Medical Assistance	
United Kingdom	In the United Kingdom, agent-based modeling was utilized to optimize the functioning of the National Health Service (NHS) during emergencies such as the COVID-19 pandemic. The implementation of such models increased the efficiency of resource allocation, particularly in the distribution of vaccines, and significantly reduced patient wait times for emergency medical assistance.
3. Urban Networks and Transport Management:	
Singapore; London (United Kingdom)	In Singapore and London, architecture-oriented agent-based models (AOAM) have been applied to predict and manage traffic flows. These models help reduce transportation delays, alleviate congestion, and improve the coordination of stakeholders in case of emergencies or unforeseen situations.
4. Emergency Response and Evacuation:	
Japan, USA	In Japan, following the devastating 2011 earthquake and tsunami, AOAM was employed to manage evacuation efforts based on real-time data analysis and predictive modeling. This approach helped authorities and rescue teams accelerate evacuation processes and minimize time delays, ultimately ensuring the maximum number of lives saved. In the United States, AOAM is used to manage evacuations during hurricanes, where it is crucial to predict the behavior of large populations and ensure the rational distribution of rescue resources based on priorities [12].
5. Urban Development and Construction Planning:	

China	In China, Architecture-Oriented Agent-Based Modeling (AOAM) was applied to the planning of a new district in Tianjin. AOAM enabled the optimization of spatial management through the rational design of transport hubs, residential areas, and industrial zones. This led to improved efficiency in the use of transport, industrial, and social infrastructure.
6. Crisis Management in Military Operations:	
USA, Israel, EU, South Korea	In the United States, Joint All-Domain Command and Control (JADC2) has been used to manage the evacuation of the wounded from conflict zones, such as in Iraq, using unmanned systems and GIS data; During operations in Gaza and other conflict zones, Israel employed elements of agent-based planning to coordinate the evacuation of civilians. The Home Front Command played a crucial role in ensuring that evacuation efforts were synchronized, utilizing predictive analytics and real-time information to manage evacuation routes and resources; In the European Union, the Copernicus Emergency Management Service (EMS) has been deployed to coordinate humanitarian operations and evacuations during natural disasters such as earthquakes, floods, and fires; South Korea utilizes elements of AOAM in its Smart Command System (SCS) to manage the evacuation of civilians and the provision of emergency assistance during disasters and military threats from North Korea [13, 14, 15].

The next step of our research will involve a parametric evaluation of the advantages and disadvantages of Agent-Based Models (ABM), Multi-Agent Models (MAM), and Architecture-Oriented Agent-Based Models (AOAM) in order to justify the selection of the most optimal model for managing evacuation operations and providing emergency assistance during active military conflicts (Table 3).

Table 3

Parametric Characteristics of Advantages and Disadvantages of Models: ABM, MAM, and AOAM

Model	Advantages	Disadvantages
Agent-Based Models (ABM)	- Suitable for analyzing individual agent behavior in uncertain environments. - Primarily used to explore optimal solutions where autonomous agent adaptation to changing environmental conditions is crucial.	- Lacks a clear hierarchical structure for coordinating actions across multiple levels. - Does not ensure a hierarchical structure of interactions, which is crucial in crisis management or military operations.
Multi-Agent Models (MAM)	- Capable of modeling complex interactions between various agents providing assistance for evacuation and emergency medical aid during military operations. - Can apply different elements of integration and interaction, ensuring the coordination of entities and resources in specific crisis situations.	- MAM may encounter the problem of decentralized control, where agents make too many autonomous decisions, which is not always efficient, for example, in military logistics.. - It does not always provide a clear hierarchical management structure or "top-down" directives, which can be critical in situations requiring centralized decision-making and coordination.
Architecture-Oriented Agent-Based Model (AOAM)	- Optimally suited for tasks requiring hierarchical connections between various participants—	- Requires a well-organized interaction structure, which can complicate implementation in

	military units, different rescue services, emergency medical services, transportation departments, and more. - Provides centralized control and decision-making capabilities, allowing for the adaptation of solutions based on rapidly changing conditions (e.g., weather, military movements) - Allows for rapid adaptation to situations, especially in scenarios where it is crucial to make priority-based management decisions using real-time operational data. The model facilitates the redirection of resources and provides subsequent coordination through central or regional command centers.	rapidly changing situations where public order coordination is disrupted. - May be more complex to implement compared to other types of modeling, as it demands detailed architecture and hierarchical relationships for effective coordination and response management.

Based on the results of our analysis of publications that document the application of Architecture-Oriented Agent-Based Models (AOAM) for solving various tasks, we have come to the well-founded conclusion that for managing the evacuation of victims and providing emergency medical assistance in conflict zones, AOAM is the most rational modeling approach.

Below are the results of the analysis of the significance of AOAM's advantages, ranked according to their importance:

1. Hierarchical Coordination and Centralized Management.

Significance: Maximum - ★★★★★

Description: AOAM provides a clear hierarchical interaction structure that allows for coordination at multiple levels—from the central level, carried out by higher governmental bodies (e.g., transport and logistics coordination through the Ministry of Transport), to the local level (e.g., coordination between emergency medical teams). This is particularly critical in crisis situations, where strict adherence to protocols and templates is required to effectively manage processes such as providing emergency medical assistance to victims of radiation exposure. The model ensures that all levels of the hierarchy work in harmony, following centralized commands while allowing for real-time data integration to inform decisions.

Argument: Unlike traditional agent-based models, where key agents may operate autonomously, in AOAM, a group of designated agents at the local level cannot carry out their functions without coordinating their actions with the central authority.

2. Flexibility and Adaptability of Agent Behavior.

Significance: Strong - ★★★★

Description: In AOAM, agents can adapt their management decisions based on real-time data about changes in conditions and/or circumstances. This adaptability either expands their capacity for effective management or constrains it to a minimum, while still adhering to the overarching architectural system of management.

Argument: Unlike traditional models, where agent behavior may become overly autonomous and uncoordinated, in AOAM agents operate within a framework of synchronization and coordination, both among themselves and with the central authority. They retain the ability to adapt to changing circumstances, transferring responsibility as needed. This ensures that the system remains flexible while maintaining overall control, enabling prompt and adaptive management in response to evolving situations.

3. Optimization of Resource Use in Conditions of Resource Scarcity and Limited Time.

Significance: Strong - ★★★★

Description: In AOAM, the continuous updating of real-time data about the current situation allows for priority-based resource management, which is grounded in the optimal distribution of available resources (e.g., blood supplies, ventilators, specific medications). The system is built on a pre-planned resource allocation structure that ensures that critical resources are distributed where they are most needed. This prevents disparities in resource allocation across regions and ensures that essential resources are efficiently delivered to areas of highest demand.

Argument: In emergency situations, it is crucial to maintain priority in resource management, especially when resources are scarce and delivery times are constrained. Unlike other models that may focus on individual agent actions, AOAM enables the coordination of actions at the subsystem level within the overall management framework. This allows agents to act in alignment with prioritized objectives in crisis management, ensuring that interrelated actions are regulated in a coordinated manner, minimizing resource waste and optimizing response times.

4. Support for Decision-Making in the Shortest Time.

Significance: Strong - ★★★★

Description: AOAM integrates seamlessly with GIS data (satellite imagery, drone data, sensors), enabling the system to adjust plans, such as the evacuation of the wounded from battlefields, almost instantaneously based on changes in enemy activity or weather forecasts. This capability allows the model to dynamically react to real-time events and update its decision-making processes accordingly, ensuring that the most up-to-date information is always guiding the response efforts.

Argument: Unlike static models, AOAM utilizes continuous streams of updated data to inform and refresh the decisions made by agents. This makes the system much more dynamic, enabling rapid crisis management and allowing for operational control to be exercised in real-time.

5. Multilevel Coordination System (Higher, Middle, and Lower Levels)

Significance: Medium - ★★★

Description: AOAM can simultaneously coordinate the actions of agents at the local level (for example, coordinating multiple ambulances to provide emergency medical aid to the population affected by a missile strike) and at the higher level (such as coordination between rescue services, military units, and medical teams).

Argument: Unlike other models, AOAM builds a coordination system that supports decision-making processes across different levels in both top-down and bottom-up directions. This makes the model more flexible and scalable when addressing the consequences of emergency situations.

6. Distribution of Decisions and Priority Management..

Importance: Medium - ★★★

Description: In an AOAM (Architecture-Oriented Agent Model), the system can automatically set priorities for various actions by agents or for decisions made by them. For example, the system can determine which logistical routes would be optimal for evacuating the population and which can be used for delivering resources and equipment. In this situation, factors such as the condition of the transport and logistics infrastructure, the availability of specific types of transport vehicles, the characteristics of delivery routes, and other relevant factors will be taken into account.

Argument: Unlike other types of models, which may operate in a decentralized manner, AOAM provides a centralized task distribution management system that takes rationality into account, reducing time losses and optimizing the process of achieving the set objectives.

7. Modeling Complex Procedures and Agent Interaction in Uncertainty.

Importance: Medium - ★★★

Description: AOAM allows for modeling complex stages of evacuating the injured and providing specific emergency medical assistance (for instance, in the case of chemical weapons use), as well as modeling agent interaction under uncertain conditions. This can be useful for identifying unforeseen situations and assessing potential risks.

Argument: Other models focus on individual agent behavior, making it difficult to create a systemic picture of interactions. AOAM analyzes the collective behavior of agents within an overall system, enabling more accurate predictions of the consequences of decisions made.

8. Integration with Geospatial Analysis and Machine Learning.

Importance: Low - ★★

Description: AOAM can easily integrate with GIS and ML, enhancing its ability to broaden the focus of decisions and the scale of its analytical base.

Argument: Unlike basic agent-based models, AOAM is easily scalable through the use of advanced data analysis technologies, making it more powerful for emergency response in complex conditions.

The above parametric comparative analysis of various model types—AOAM, Multi-Agent Modeling (MAM), and Agent-Oriented Modeling (AOM)—leads us to conclude that AOAM is the optimal choice, as it fully aligns with the tasks of rapid response and crisis management operations under limited resource conditions [17, 20, 21].

3. AOAM Structure: Development and Implementation.

3.1. Organizational Management Structure of AOAM

The mathematical formalization of an Architecture-Oriented Agent Model (AOAM) for managing the evacuation of the population and the wounded, as well as providing emergency medical assistance at various levels of hierarchy (national, regional, local), must account for the interconnection of key interacting agents, resource management, and transportation logistics management at all levels. The model can be described using a multi-level complex management structure, where each hierarchical level is represented by key agents performing their clearly defined functions. Simultaneously, all agents are interconnected through centralized coordination via information exchange, as well as data on weather conditions, material, technical, transportation, infrastructure, and other resource provisions.

The main bodies and structures of AOAM that interact with each other to organize and manage the transportation and evacuation of affected populations and the wounded from active combat zones should, as mentioned earlier, function as agents within the structure at the highest level of the hierarchy:

1. *The National Security and Defense Council (NSDC),* which coordinates all processes related to national security, including the protection of the population and crisis management. This body has the authority to initiate strategic initiatives that require interagency cooperation.

2. *The Ministry of Defense* is responsible for managing military operations and can act as the coordinator for the evacuation of the wounded and the provision of first medical aid in combat zones.

3. *The Ministry of Health* is responsible for coordinating medical services and managing healthcare systems in crisis situations. This agent must ensure the medical component of the model, including managing the transport logistics of ambulance teams, distributing resources (such as blood supplies, medications, equipment, and personnel), and coordinating with other agencies.

4. *The State Emergency Service (SES)* manages emergency operations and coordinates rescue services, overseeing the evacuation process and providing assistance to affected populations. Through the implementation of AOAM as an emergency response and coordination module, SES can ensure effective interaction with other services (military, medical, and civilian) to address the complex tasks of evacuation and emergency aid in combat conditions, where civilian services may lack the necessary expertise.

5. *The Central Operational Command (e.g., the General Staff of the Armed Forces)* is responsible for the operational management of military actions and the coordination of troops in the field. In the described situations, it can, in emergencies, deploy military equipment and personnel for the transportation of resources, as well as for the evacuation of the population (including the provision of emergency medical assistance by military doctors). This can be implemented through AOAM in conditions of destroyed infrastructure (damaged roads, bridges, and railways), allowing the system to adapt to local-level conditions.

6. *Crisis Management Centers* oversee all aspects of crisis response and coordinate with military, medical, and civilian services.

7. *The Ministry of Transport* manages transportation logistics and coordinates the activities of relevant transport sectors during emergencies. In crisis situations, it oversees transport logistics and works closely with the State Emergency Service (SES) and medical services to find optimal solutions for evacuating the civilian population and transporting them to receive medical assistance.

8. *The Hydro-Meteorological Center* manages the process of processing and transmitting meteorological data to the coordination and management center for planning evacuation and rescue operations and forecasting needs based on weather changes.

9. *International organizations,* such as the UN, Red Cross, and NATO, can play a crucial role in implementing management decisions related to evacuation from disaster zones, such as in the case of the destruction of the Kakhovka Dam and the flooding of a large area.

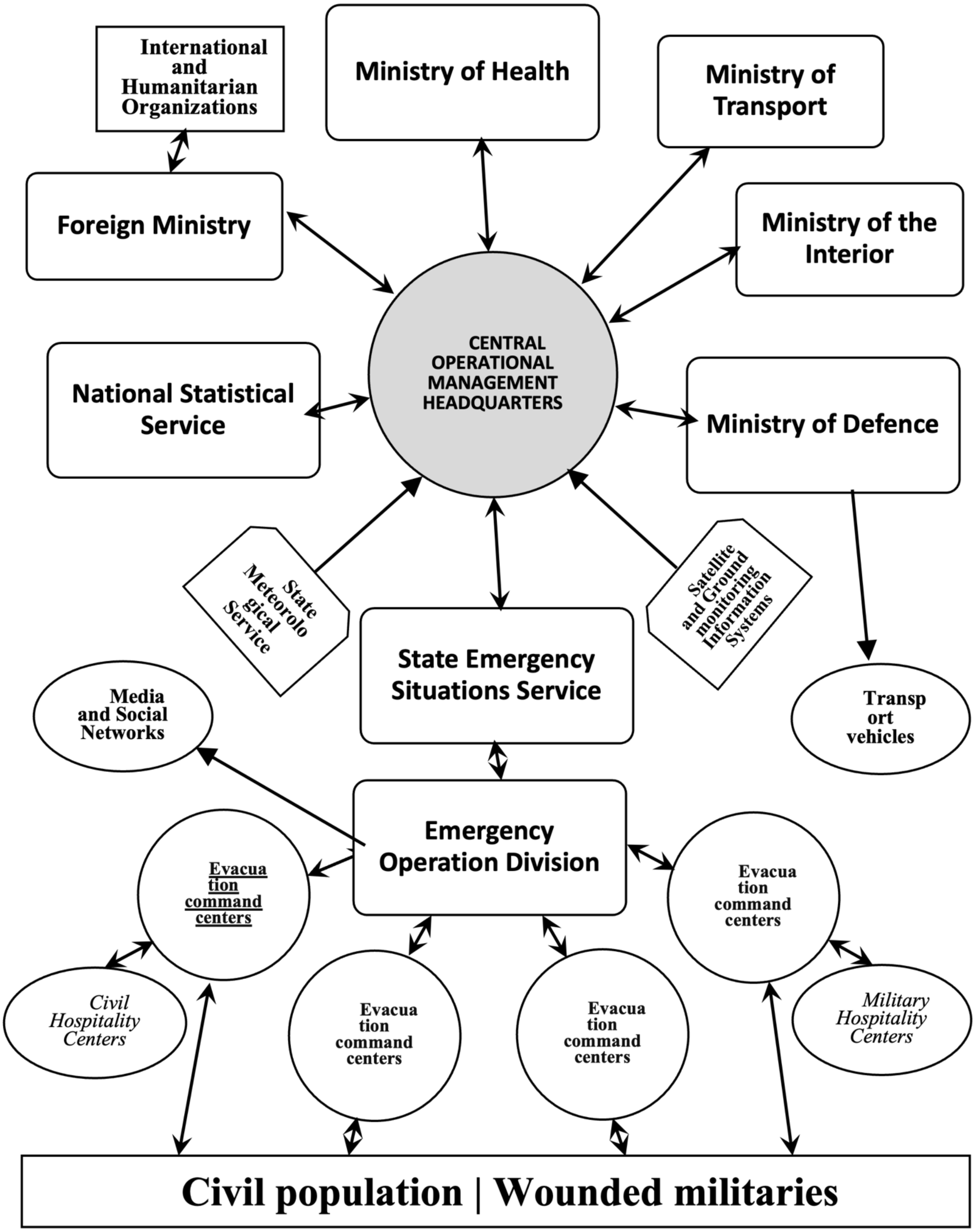

Figure 1: Proposed AOAM for Implementation: Organizational Management Structure Highlighting Key Interacting Agents

Additionally, these organizations can provide humanitarian aid, organize "humanitarian corridors," and, at the request of the government, conduct assessments of the situation and the consequences of the disaster.

3.2. The Role of GIS in the AOAM Structure

Geographic Information Systems (GIS) play a crucial role in the proposed Architecture-Oriented Agent Model (AOAM) by enabling the rapid adaptation of the transportation evacuation and emergency medical assistance management mechanisms during crisis situations and military conflicts. Essentially, GIS serves as the "eyes in the sky." Its use significantly enhances operational management efficiency by providing geospatial data and real-time analysis of its changes [23].

Thus, satellite data, particularly from sources like NASA FIRMS, can be integrated into GIS and play a crucial role in analyzing geographic information necessary for crisis management, such as dealing with fires and organizing evacuations from these zones.

It is important to note that GIS collects and integrates data from various sources to create a comprehensive observation framework, supporting effective decision-making. As a structural element integrated into AOAM, GIS allows for the accumulation, processing, and transmission of relevant data to the central command. This includes geospatial data with information about the location of objects, terrain topography, infrastructure conditions (roads, bridges, buildings), active conflict zones, and other spatial characteristics. These data are essential for planning evacuation routes, selecting evacuation zones, and locating emergency medical assistance facilities [24, 25].

We particularly want to emphasize the fact that GIS is proposed for integration into AOAM to optimize transportation evacuation routes. It provides constantly updated information on distances, transportation hubs, road conditions, and alternative routes, which helps minimize evacuation time and ensure safe movement.

One of the most critical aspects is that GIS provides interactive maps and visualization tools that enable coordination centers and operators to see the situation in real-time, which ensures effective decision-making at various levels of management. This also helps rescuers quickly and accurately assess the situation, adjust routes, and prevent emergency situations on the roads.

In the context of managing emergency medical logistics, it is crucial to have data on the affected population, including: demographic data of the victims, their distribution across the territory, their concentration in specific locations, age groups, injury severity, the number of victims, and vulnerable population categories (children, the elderly).

Meteorological data is also of primary importance for adaptive operational management, including information on current and forecasted weather conditions such as precipitation, wind speed, and temperature, which may lead to route changes and adjustments in evacuation conditions as well as aid provision to the victims. It is also necessary to consider the possibility of extreme weather events, such as hurricanes, floods, blizzards, etc.

For areas affected by military aggression, security and military threat data are particularly important. This involves managing transportation evacuations from risk zones: GIS allows for the assessment of the nature and degree of such risks. Additionally, the system enables the tracking of changes in conflict zones, troop movements, and adjustments to transport and logistics routes considering checkpoints, minefields, and other military-related factors.

Equally important is the data transmitted from drones and sensor systems. These are used to supplement information for assessing the condition of affected areas and infrastructure, such as bridges, dams, and critical infrastructure. The data also help evaluate the feasibility of using these assets for providing emergency medical aid to the injured and wounded. Sensor systems, for example, can detect chemical or radiation contamination, which necessitates substantial adjustments in managing rescue operations.

GIS also transmits logistics data to the management coordination center, including the location of transport depots, warehouses, the availability of access routes, and the positioning of cargo trucks and ambulances on the roads. All of this information serves for the rapid response to changes in the situation and the corresponding decision-making by the relevant structures.

Predictive analytics obtained through GIS play a strategic role in effectively managing such operations. The practical application of scientific approaches and simulation models allows for the most accurate prediction of future events, such as new infrastructure damage due to weather changes or troop movements.

One of the significant aspects is the ability to receive feedback and adapt emergency aid scenarios/routes in the shortest possible time. As soon as the situation changes (for example, a mass missile strike or the destruction of a bridge), GIS updates the data, and AOAM instantly responds by offering alternative scenarios or transport-logistical routes.

GIS technologies significantly enhance the efficiency of managing routes for providing assistance to victims and delivering emergency aid by supplying up-to-date information on road conditions, risk predictions, and resource deployment possibilities. These systems help adjust routes, manage workload, and improve coordination between various services during emergency situations [28].

3.3. The mathematical formalization of an Architecture-Oriented Agent Model (AOAM)

The proposed AOAM with an integrated Geographic Information System (GIS) includes several key components that reflect the efficiency of managing evacuation processes and providing emergency medical assistance. These components are as follows:

Overall Structure of AOAM with GIS.

Agents *(A_i)* represent management entities that coordinate their actions based on data received from the GIS.

$$Ai=\{Ri,Ci,Di,Pi\}, \tag{1}$$

where:

Ri - available resources of the agent (e.g., ambulances, transportation),

Ci - the current state of the agent (e.g., location, readiness),

Di - data obtained from GIS,

Pi - the agent's priorities in fulfilling responsibilities.

Geospatial data, when integrated with GIS in the Architecture-Oriented Agent Model (AOAM)

$$G(i)=\{Dr(i), Dw(i), Drz(i), Dd(i)\} \tag{2}$$

where:

Dr(i) - data about the condition of roads and transport hubs,

Dw(i) - weather conditions (precipitation, wind, temperature),

Drz(i) - data about risk zones (combat zones, checkpoints, minefields),

Dd(i) - data about the demographic situation (distribution of affected people).

The objective function for route optimization.

In the context of AOAM (Architecture-Oriented Agent Model) integrated with GIS can be formulated as a minimization problem aimed at reducing the time required to complete operations such as evacuating victims and delivering medical resources. This objective function considers various factors like travel time, road conditions, risks, and resource availability, all derived from real-time GIS data.

$$\min Tij=\sum^{L}{}_{k=1} (gik(1+rk))/vk \tag{3}$$

where:

Tij — time to deliver from point i to point j,

gik — distance between points on the route,

rk — risk level on the section (e.g., road damage, dangerous zone),

vk — speed of movement on the section.

Optimization of Resource Distribution..

In AOAM with integrated GIS, a crucial factor is the optimization of resource distribution (medical teams, transport vehicles, medications) based on data regarding the condition of affected individuals in a specific area. This task can be described as a moderate maximization of the utilization of available resources.:

$$\max Erd=\sum^{N}_{l=1} (Ri\bullet Vi)/Ti \tag{4}$$

where:

Erd – total efficiency of resources distribution,

Ri – number of available resources in the locale (e.g., a medical team)

Vi – number of victims or persons in need of assistance in the locale,

Ti – the time required to get the resources to the locate.

Feedback and Rapid Adaptation.

The GIS system allows for real-time feedback, which helps adjust the actions of agents based on changes at the site of the emergency. This enables the implementation of immediate management actions to provide emergency assistance to those affected.

$$A_i(m+1)=A_i(m)+\Delta R_i \bullet \phi(D_i(m)) \tag{5}$$

where:

Ai(m+1) – an agent's activity at the next point in time, according to the data changes,

Δri – available resources changes б

ϕ(Di(m)) – function of capture new GIS data received (e.g., destruction or cataclysmic impact)

Evaluation of System Efficiency

Total efficiency of the AOAM system with integrated GIS can be reflected in the efficiency of the target function Eevac, which monitors evacuation tasks, the quality of medical care and the speed of first response.

$$E_{sys} = \alpha\bullet E_{evac} + \beta\bullet E_{med} + \gamma\bullet E_{adap} \tag{6}$$

where:

Eevac – evacuation efficiency,

Emed – medical assistance efficiently,

Eadap – system adaptive response to new data changes,

α,β,γ – weighting coefficients for the level assessment of each aspect [26, 27].

3.4. Implementation of the Integrated AOAM: Challenges and Opportunities.

The implementation of the proposed AOAM in the context of counteracting the aggressor's military actions is associated with several significant challenges. These challenges relate to technical and organizational aspects, as well as factors of national governance and crisis coordination. The key difficulties that can be highlighted during the implementation of AOAM include:

Technical Challenges of Data Collection, Processing, and Transmission:

At the initial stages of the project, AOAM will require data from a wide variety of sources (drones, satellites, data on military operations, transportation, and medical supplies). Integrating, processing, and utilizing this data requires significant technical effort, especially given the heterogeneity of data streams coming from different systems with various formats and update rates. Consolidating such diverse data streams poses a major challenge [31, 32].

Ensuring Reliable and Secure Communication Channels. In the context of ongoing military actions and unstable conditions, establishing reliable communication channels could become a critical issue, particularly when transmitting large volumes of data. In this regard, ensuring information security becomes one of the most sensitive aspects of project implementation. Since AOAM involves handling sensitive data, such as military troop movements, civilian evacuations, and distributed resources, potential cyberattacks or data breaches could have catastrophic consequences in a combat environment.

Additionally, ensuring backup communication channels in case of failures or attacks is essential.

A major bottleneck in the project is the current lack of coordination between relevant higher government structures. AOAM requires synchronized interaction between military bodies, ministries, and agencies responsible for managing civilian and military rescue operations. Organizing effective cooperation between these structures at all levels of the management system is one of the most challenging tasks in implementing AOAM. Conflicting interests must also be considered, as various structures may have differing goals and priorities, complicating their alignment. Furthermore, issues of operational compatibility between systems may arise, as different agencies might use incompatible systems, making integration into the core AOAM architecture difficult.

Another critical issue is the coordination of transport and logistics operations, especially during the early stages of project implementation. This becomes more complex when considering the use of different types of transportation under ongoing military operations and damaged infrastructure.

The most critical challenge in the successful implementation of the proposed AOAM is power outages and communication failures. With continuous missile attacks and energy resource shortages, it becomes exceedingly difficult to ensure stable power supply and communication for the smooth operation of all interacting agents involved in emergency aid processes.

In the moderate complexity category of AOAM implementation challenges is the need to train a large number of personnel familiar with the specifics of military operations management, transport logistics, and emergency medical assistance.

This group of problems and challenges also includes resistance to implemented changes. The fact is that personnel may sabotage the introduction of new technology, especially if there is already an established system of operations in place. Resistance to change can arise from a reluctance to adapt to new systems, lack of confidence in the technology, or fear of disrupting existing workflows.

Another issue in implementing the integrated model is the limitations in computational power. Processing vast amounts of data during the initial stages requires significant computational resources, especially when complex models for learning and predictive analytics are used.

The overall set of "bottlenecks" in the implementation of AOAM also includes the problems of scalability and flexibility to ensure the system can adapt to different crisis scenarios. This involves the need to modify the system depending on the actual availability of data, the number of interacting agents, and the specific challenges of emergency response operations. It is particularly challenging to create a system that functions efficiently in both localized and large-scale scenarios, such as massive evacuations or the provision of specific emergency aid (e.g., in the case of fires). Therefore, the system must be flexible enough to adapt to the emergence of new circumstances and limitations [35].

One of the significant problem areas in the implementation of the project is the high overall cost. The development and deployment of AOAM require substantial financial investments in equipment, software, personnel training, and technical support. In addition to the initial system costs, there are considerable ongoing expenses for maintenance, including ensuring security, providing technical support, and system upgrades.

According to the authors of this study, the implementation of the proposed model can be supported by external donors, international financial and other organizations, as well as large corporations aiming to test and improve the advanced technologies they have developed. Through cooperation, private partnerships, and the use of existing technologies, even with limited resources in Ukraine, it may be possible to introduce adapted versions of AOAM.

We believe that under conditions of limited financial resources and ongoing military conflict, the most rational approach would be a modular implementation of AOAM, utilizing international assistance, partnerships with the private sector, as well as cloud technologies and open-source solutions to minimize costs. This approach would allow for the initial deployment of the most critical system components, gradually improving their functionality, while ensuring flexibility and adaptation to changing circumstances [40, 42].

4. Discussion and Future Directions

Despite the wide range of issues explored regarding the practical application of architecture-oriented agent modeling (AOAM), several problem areas remain insufficiently studied and could become the subject of deeper research. One such aspect is the exploration of the practical integration of IoT systems into the model. This is particularly important for coordination activities within AOAM. It will be especially significant in managing remediation operations after the cessation of military activities. The integration of IoT could enhance data collection and expand the functional capabilities of AOAM in the comprehensive remediation of contaminated areas in Ukraine [50].

5. Conclusions

In summary, it is worth noting that the integration of GIS into AOAM enhances the management of evacuation processes and medical assistance by optimizing routes, dynamically distributing resources, and enabling a system of adaptation based on real-time data updates. The mathematical models underlying this system capture all aspects of the complex interaction of agents at every level of the management hierarchy, making the proposed model an effective tool for crisis management.

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.

7. Acknowledgements

We thank the anonymous reviewers, scientific editors, and editors for their valuable comments and recommendations.

References

[1] Kupriyanov, S. & Chernikov, O. & Zhukov, A. & Pluzhnik, M. & Nazarov, I.. (2024). Research perspectives outlined in international publications analyzing medical aid and evacuation measures in emergency (armed conflicts). Medico-Biological and Socio-Psychological Problems of Safety in Emergency Situations. 2024. (1); 94-107. doi: 10.25016/2541-7487-2024-0-1-94-107.

[2] Bricknell MC, Johnson A Forward Medical Evacuation BMJ Military Health 2011;157:S444-S448. doi: 10.1136/jramc-157-4s-07.

[3] Bagg, Mark R. MD, MC, USA, COL; Covey, Dana C. MD, MC, USN, CAPT; Powell, Elisha T. IV MD, MC, FS, USAF, COL. Levels of Medical Care in the Global War on Terrorism. Journal of the American Academy of Orthopedic Surgeons 14(10):p S7-S9, October 2006. doi: 10.5435/00124635-200600001-00003.

[4] Filho, «Comparative Analysis of Patterns: Distinctions and Applications of Behavioral, Creational, and Structural Patterns», Zenodo, сен. 2024. 1-6. doi: 10.5281/zenodo.13765052.

[5] Marius Neuwirth, Tobias Fleiter, René Hofmann et al. Towards high-resolution modelling of energy-intensive industries: An agent-based process diffusion approach with georeferenced industry sites, 19 August 2024, PREPRINT (Version 1) available at Research Square. doi: 10.21203/rs.3.rs-4381601/v1.

[6] Leone R, Whitaker J, Homan Z, et al Framework for the evaluation of military health systems BMJ Mil Health 2023;169:280-284. doi:10.1136/bmjmilitary-2020-001699.

[7] T. Moghaddam, Mahyar. (2020). IoT-based Emergency Evacuation Systems. doi:10.48550/arXiv.2005.13374.

[8] Bricknell M, Horne S. Personal view: security sector health systems and global healthBMJ Mil Health 2023;169:e64-e67. doi: 10.1136/bmjmilitary-2020-001607.

[9] Khalili, S.M.; Mojtahedi, M.; Steinmetz-Weiss, C.; Sanderson, D. A Systematic Literature Review on Transit-Based Evacuation Planning in Emergency Logistics Management: Optimisation and Modelling Approaches. Buildings 2024, 14, 176. doi:10.3390/buildings14010176.

[10] Čech, P.; Mattoš, M.; Anderková, V.; Babič, F.; Alhasnawi, B.N.; Bureš, V.; Kořínek, M.; Štekerová, K.; Husáková, M.; Zanker, M.; et al. Architecture-Oriented Agent-Based Simulations and Machine Learning Solution: The Case of Tsunami Emergency Analysis for Local Decision Makers. Information 2023, 14, 172. doi: 10.3390/info14030172.

[11] Juřík, Vojtěch & Uhlík, Ondřej & Snopková, Dajana & Kvarda, Ondřej & Apeltauer, Tomas & Apeltauer, Jiří. (2023). Analysis of the use of behavioral data from virtual reality for calibration of agent-based evacuation models. Heliyon. Volume 9, Issue 3. doi: 10.1016/j.heliyon.2023.e14275.
[12] Abdelshafie, Alaa. (2020). Crisis Management and Logistics of international security system in Regional Organizations. Materials of International Conference on Economics and Business Management. Proceeding of IASTEM, P.12-21.
[13] Summary Of Tl-Ie Joint All-Domain Command & Control (_JADC2) Strategy. 2022. URL: https://media.defense.gov/2022/Mar/17/2002958406/-1/-1/1/SUMMARY-OF-THE-JOINT-ALL-DOMAIN-COMMAND-AND-CONTROL-STRATEGY.pdf.
[14] Jennifer, Meas. (2024). The Strategic Landscape of AI: A Guided Service for Industry Leaders, Decision Makers, and Federal Agencies. URL: https://www.leadershipconnect.io/federal-government/the-strategic-landscape-of-ai-a-guided-service-for-industry-leaders-decision-makers-and-federal-agencies/.
[15] Home Front Command for the Citizens of Israel. Home Front Command. 2017. URL: https://www.idf.il/en/mini-sites/regional-commands/home-front-command/home-front-command/.
[16] Helbing, D., Farkas, I.J., Vicsek, T. (2002). Crowd Disasters and Simulation of Panic Situations. In: The Science of Disasters. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-56257-0_11.
[17] Vu, Tuong Manh, Probst, Charlotte, Nielsen, Alexandra, Bai, Hao, Meier, Petra S., Buckley, Charlotte, Strong, Mark, Brennan, Alan and Purhouse, Robin (2020) 'A Software Architecture for Mechanism-Based Social Systems Modelling in Agent-Based Simulation Models' Journal of Artificial Societies and Social Simulation 23 (3) 1. URL: http://jasss.soc.surrey.ac.uk/23/3/1.html. doi: 10.18564/jasss.4282.
[18] Almeida, João & Rossetti, Rosaldo & Coelho, António. (2013). Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems. URL: https://arxiv.org/abs/1303.4692. doi:10.48550/arXiv.1303.4692.
[19] Gelenbe, Erol & Wu, Fang-Jing. (2012). Large scale simulation for human evacuation and rescue. Computers & Mathematics with Applications. Volume 64, Issue 12. 3869–3880. URL: https://www.sciencedirect.com/science/article/pii/S0898122112002611. doi: 10.1016/j.camwa.2012.03.056.
[20] Insani, N.; Taheri, S.; Abdollahian, M. A Mathematical Model for Integrated Disaster Relief Operations in Early-Stage Flood Scenarios. Mathematics 2024, 12, 1978.. doi: 10.3390/math12131978.
[21] Yang, Xiangmin & Liu, Yuelin & Majumdar, Arnab & Grass, Emilia & Ochieng, Washington. (2024). Characteristics of crowd disaster: Database construction and pattern identification. International Journal of Disaster Risk Reduction. Volume 111. 2024. URL: https://www.sciencedirect.com/science/article/pii/S2212420924004151. doi: 10.1016/j.ijdrr.2024.104653.
[22] Md. Shalihin Othman and Gary Tan. 2024. A Prescriptive Simulation Framework with Realistic Behavioural Modelling for Emergency Evacuations. ACM Trans. Model. Comput. Simul. 34, 1, Article 4 (January 2024), 24 p. URL: https://dl.acm.org/doi/10.1145/3633330. doi: 10.1145/3633330.
[23] Jazbec, Anja. (2024). Geospatial Artificial Intelligence (GeoAI) and GIS in Building Damage Assessment and Accessibility to Neighborhood Parks: A McDonough County Study. doi: 10.1016/j.ijdrr.2024.104653.
[24] Trofymchuk, O.; Klymenko, V.; Anpilova, Y.; Sheviakina, N.; Zagorodnia, S. The aspects of using GIS in monitoring of environmental components. Int. Multidiscip. Sci. GeoConf. SGEM 2020, 20, 581–588. doi:10.5593/sgem2020/2T/s08.075.
[25] Muraoka, H.; Ishii, R.; Nagai, S.; Suzuki, R.; Motohka, T.; Noda, H.M.; Hirota, M.; Nasahara, K.N.; Oguma, H.; Muramatsu, K. Linking Remote Sensing and In Situ Ecosystem/Biodiversity Observations by "Satellite Ecology"; Springer: Tokyo, Japan, 2012; pp. 277–308. URL:

https://link.springer.com/chapter/10.1007/978-4-431-54032-8_21. doi:10.1007/978-4-431-54032-8_21.
[26] I. Y. Muttaqien, S. Tanugraha, J. E. Puspitaningrum, and H. A. W. Manik, “Evaluation of Emergency Access Evacuation Routes Using Agent-Based Model Application”, JARINA, vol. 3, no. 2, pp. 71–80, Aug. 2024. doi: 10.24002/jarina.v3i2.8308.
[27] Wang, C.; Zhu, C.; Xiao, K.; Tang, Y.; Zhen, H. Visualization of Emergency Evacuation Physical Behavior under Multi-Agent Decision-Making. Appl. Sci. 2023, 13, 5509. doi:10.3390/app13095509.
[28] Mendoza, Gil & Martins, Helena. (2006). Multi-Criteria Decision Analysis in Natural Resource Management: A Critical Review of Methods and New Modelling Paradigms. Forest Ecology and Management. 230. 1-22. doi: 10.1016/j.foreco.2006.03.023.
[29] Deng, K.; Zhang, Q.; Zhang, H.; Xiao, P.; Chen, J. Optimal Emergency Evacuation Route Planning Model Based on Fire Prediction Data. Mathematics 2022, 10, 3146. doi: 10.3390/math10173146.
[30] Cui, Jianxun, An, Shi, Zhao, Meng, A Generalized Minimum Cost Flow Model for Multiple Emergency Flow Routing, Mathematical Problems in Engineering, 2014, 832053, 12 p, 2014.. doi: 10.1155/2014/832053.
[31] Hai, Sun & Han, Guorui & Zhang, Xiaowei & Ruan, Xuejing. (2024). Grasping Emergency Dynamics: A Review of Group Evacuation Techniques and Strategies in Major Emergencies. Journal of Safety Science and Resilience. URL: https://www.sciencedirect.com/science/article/pii/S2666449624000628. doi: 10.1016/j.jnlssr.2024.05.006.
[32] Hornos, Miguel J. and Zamudio-Rodríguez, Víctor Manuel. ‘Sensing, Decision-making and Economic Impact for Next-generation Technologies’. 1 Jan. 2024 : 271 – 274.. URL: https://content.iospress.com/articles/journal-of-ambient-intelligence-and-smart-environments/ais246004. doi: 10.3233/AIS-246004.
[33] Ding, Yifei & Zhang, Yuxin & Huang, Xinyan. Intelligent Emergency Digital Twin System for Monitoring Building Fire Evacuation. Journal of Building Engineering. Volume 77, 2023. URL: https://www.sciencedirect.com/science/article/pii/S2352710223015966. doi: 10.1016/j.jobe.2023.107416.
[34] J. Jiang, W. Tu, H. Kong, W. Zeng, R. Zhang and M. Konecny, "Large-Scale Urban Multiple-Modal Transport Evacuation Model for Mass Gathering Events Considering Pedestrian and Public Transit System," in IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 12, pp. 23059-23069, Dec. 2022. URL: https://ieeexplore.ieee.org/document/9901464. doi: 10.1109/TITS.2022.3198178.
[35] Mondragon Regalado, J.R., Arbulú Pérez Várgas, C.G. (2021). Decision Support Systems in Disaster Risk Management Policies for Adaptation to Climate Change. In: Stephanidis, C., Antona, M., Ntoa, S. (eds) HCI International 2021 - Posters. HCII 2021. Communications in Computer and Information Science, vol 1421. Springer, Cham. doi: 10.1007/978-3-030-78645-8_64.
[36] Rodrigo Ternero, Guillermo Fuertes, Miguel Alfaro, Manuel Vargas, Jorge Sabattin, Sebastian Gutierrez, Claudia Duran, Artificial intelligence methodologies for building evacuation plan modeling, Journal of Building Engineering. Volume 96. 2024. URL: https://www.sciencedirect.com/science/article/pii/S2352710224019764. doi: 10.1016/j.jobe.2024.110408.
[37] Linjiang Zheng, Xiaoli Peng, Linglin Wang, Dihua Sun, Simulation of pedestrian evacuation considering emergency spread and pedestrian panic, Physica A: Statistical Mechanics and its Applications, Volume 522, 2019. URL: https://www.sciencedirect.com/science/article/pii/S0378437119301359. doi: 10.1016/j.physa.2019.01.128.

[38] Alazbah, Afnan & Fakeeh, Khalid & Rabie, Osama. (2023). Enhancing Evacuation Planning through Multi-Agent Simulation and Artificial Intelligence: Understanding Human Behavior in Hazardous Environments. URL: https://arxiv.org/abs/2307.09485.

[39] Gao 高山, Shan & Chang, Chen & Liu, Qiang & Zhang, Mingming & Yu, Fei. (2023). Study on the optimization for emergency evacuation scheme under fire in university building complex. Heliyon. URL: https://www.cell.com/action/showPdf?pii=S2405-8440%2823%2901484-6. doi: 10.1016/j.heliyon.2023.e14277.

[40] Ludwig, l., & mattedi, m. A.. (2018). The information and communication technologies in the risk management of social and environmental disasters. Ambiente & Sociedade, 21, e01034. doi: 10.1590/1809-4422asoc0103r4vu18L1AO.

[41] Ruichen Ma, Ailing Huang, Zhihuan Jiang, Ziji'an Wang, Qian Luo, Xuanyi Zhang, A data-driven optimal method for massive passenger flow evacuation at airports under large-scale flight delays, Reliability Engineering & System Safety, Volume 245, 2024. URL: https://www.sciencedirect.com/science/article/pii/S0951832024000632. doi: 10.1016/j.ress.2024.109988.

[42] N. Nikhil, S. M. Shreyas, G. Vyshnavi and S. Yadav, "Unmanned Aerial Vehicles (UAV) in Disaster Management Applications," 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), Tirunelveli, India, 2020, pp. 140-148. URL: https://ieeexplore.ieee.org/document/9214241. doi: 10.1109/ICSSIT48917.2020.9214241.

[43] Zhiman Xu, Qiang Bai, Yuqi Shao, Aihui Hu, Zhi Dong, A review on passenger emergency evacuation from multimodal transportation hubs, Journal of Traffic and Transportation Engineering (English Edition), Volume 9, Issue 4, 2022. URL: https://www.sciencedirect.com/science/article/pii/S2095756422000551. doi: 10.1016/j.jtte.2022.02.001.

[44] Wang, K., Yuan, W. & Yao, Y. Rescue guiders layout study based on a two-layer optimization framework. Urban Lifeline 2, 11 (2024). doi: 10.1007/s44285-024-00023-2.

[45] A. Trabelsi, H. Ezzedine and C. Kolski, "Architecture modelling and evaluation of agent-based interactive systems," 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583), The Hague, Netherlands, 2004, pp. 5159-5164 vol.6. doi: 10.1109/ICSMC.2004.1401013.

[46] Qu, C.; Kim, E. Reviewing the Roles of AI-Integrated Technologies in Sustainable Supply Chain Management: Research Propositions and a Framework for Future Directions. Sustainability 2024, 16, 6186. doi: 10.3390/su16146186.

[47] A. Trabelsi, H. Ezzedine and C. Kolski, "Architecture modelling and evaluation of agent-based interactive systems," 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No.04CH37583), The Hague, Netherlands, 2004, pp. 5159-5164 vol.6. doi: 10.1109/ICSMC.2004.1401013.

[48] Tran, C., Ezzedine, H., Kolski, C. (2009). A Generic and Configurable Electronic Informer to Assist the Evaluation of Agent-Based Interactive Systems. In: Lopez Jaquero, V., Montero Simarro, F., Molina Masso, J., Vanderdonckt, J. (eds) Computer-Aided Design of User Interfaces VI. Springer, London. doi: 10.1007/978-1-84882-206-1_23.

[49] J. Coutaz and L. Nigay, Architecture logicielle conceptuelle des systèmes interactifs Chapitre 7 : Analyse et Conception de l'Interaction Homme-Machine dans les systèmes d'information, Hermes Publ, pp.207-246, 2001.

[50] Hryhorczuk, Daniel & Levy, Barry & Prodanchuk, Mykola & Kravchuk, Oleksandr & Bubalo, Nataliia & Hryhorczuk, Alex & Erickson, Timothy. (2024). The environmental health impacts of Russia's war on Ukraine. Journal of Occupational Medicine and Toxicology. 19

[51] Abdelwaheb, Trabelsi & Ezzedine, Houcine. (2013). Evaluation of an Information Assistance System Based on an Agent-based Architecture in Transportation Domain: First Results. URL: https://univagora.ro/jour/index.php/ijccc/article/view/312. doi: 10.15837/ijccc.2013.2.312.

[52] Tarpin-Bernard, Franck & David, Bertrand. AMF: un modèle d'architecture multi-agents multi-facettes. 1999. Vol.5. URL: http://iihm.imag.fr/tarpin/publis/tsi99.pdf.

[53] Lian, H.; Zhang, S.; Li, G.; Zhang, Y. Pedestrian Simulation on Evacuation Behavior in Teaching Building of Primary School Emergencies and Optimized Design. Buildings 2023, 13, 1747. doi: 10.3390/здания13071747.

[54] Houcine Ezzedine, Christophe Kolski, André Péninou, Agent-oriented design of human–computer interface: application to supervision of an urban transport network, Engineering Applications of Artificial Intelligence, Volume 18, Issue 3, 2005. doi: 10.1016/j.engappai.2004.09.013.

[55] Ferber, Jacques. "Les Systèmes multi-agents: vers une intelligence collective." (1995). URL: https://api.semanticscholar.org/CorpusID:59893187.

[56] Thomas B. Sheridan, Chapter 5 - Task Analysis, Task Allocation and Supervisory Control, Editor(s): Marting G. Helander, Thomas K. Landauer, Prasad V. Prabhu, Handbook of Human-Computer Interaction (Second Edition), North-Holland, 1997, Pages 87-105. doi: 10.1016/B978-044481862-1/50071-6.