CHAPTER 3

Digitalization of crisis management remediation: assessment of implementation and development prospects

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Abstract

The first quarter of the 21st century has been marked by the growth in the scale and complexity of emergencies, ranging from global climate disasters to full-scale military conflicts. All of this has created an acute need to shift from traditional crisis management methods to intelligent digital systems capable of responding rapidly, processing vast arrays of heterogeneous data, and coordinating the actions of all participants in real time. In this context, remediation in the modern world has already been established as a multifunctional process that combines the restoration of the ecological environment with the revival of socio-economic activity on the cleaned, reconstructed, and restored territory. Today, successful remediation serves not only an environmental purpose but also stimulates the return of the population, the development of entrepreneurial entities, the attraction of investments, and the strengthening of a country's international reputation. In the case of Ukraine, the digitalization of crisis management of remediation processes plays the role of a critically important factor for the efficiency and speed of post-war recovery. In the author's research, the historical and theoretical aspects of the development of the remediation concept are revealed, and a methodological framework for assessing the effectiveness of digital management based on multicriteria models and Monte Carlo simulation is presented. Particular attention is paid to the integration of IoT, AI, UAVs, digital twins, GIS, and blockchain technologies to achieve a comprehensive environmental, social, and economic recovery effect. Recommendations are formulated for the application of digital solutions in the practice of territorial remediation, with an emphasis on the prospects for maximizing Ukraine's potential.

Keywords

Remediation, digitalization, crisis management, recovery, Internet of Things (IoT), artificial intelligence (AI), digital twins, geographic information systems (GIS), unmanned aerial vehicles (UAVs), blockchain, post-war recovery of Ukraine, multi-criteria

decision analysis (MCDA), adaptive management, digital transformation, sustainability, Monte Carlo simulation, resilience.

3.1 Introduction

It should be noted that information systems and technologies at the beginning of the 21st century have become an integral part of all stages of disaster response – from monitoring and forecasting to planning recovery activities, enabling high accuracy in situation assessment, optimization of resource distribution, damage assessment, increased response speed, and coordination among participants involved in all types of operations, including the evacuation of the population, the search for affected individuals, the clearing of debris, and the delivery of critically needed equipment, materials, medicines, and more [1, 2]. Based on the analysis of recent scientific publications, the author has come to the conclusion that remediation, as a complex of various types of activities aimed at restoring territories affected by natural disasters, technological accidents, or military conflicts, is increasingly manifesting its multifunctional significance in modern scientific and practical discourse. Whereas previously remediation was regarded mainly in the context of an environmental process for eliminating different types of soil, water, and air pollution, as well as restoring natural systems, today the focus within this field has significantly expanded, and remediation is now viewed as a powerful instrument for the socio-economic revival of territories. An ecologically restored territory, after the implementation of a complex of remediation measures, becomes a foundation for the return of the population, the resumption of economic activities, the attraction of investments, the creation of new jobs, the development of entrepreneurship, and the revival of the national economy [3]. Thus, remediation acquires the nature of a multiplicative factor, directly influencing the comprehensive restoration of the ecological and socio-economic structures of territorial systems, thereby contributing to the strengthening of the overall resilience of the country. Moreover, the successful implementation of large-scale remediation projects serves as a positive reputational factor for the state, ultimately strengthening its position as, first and foremost, an environmentally responsible participant in the global community.

The relevance of this study is determined by the necessity of a comprehensive understanding of remediation in its new, expanded meaning, especially in the context of Ukraine's post-war recovery, where the consequences of destruction are not only environmental in nature but also deeply socio-economic. According to the 2024 report "Russia-Ukraine War: Environmental Impact", the area of contaminated

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land amounts to 20.8 million square meters (of which 79.3 thousand hectares represent burned forests and other vegetation, and 470.0 thousand hectares are subject to inspection and demining, author's note). The estimated damage to land resources is 27.9 billion USD, to water resources – 2.1 billion USD, and to the atmosphere – 17.7 billion USD, with these figures continuing to grow and worsen [4]. In this context, the digitalization of crisis management processes related to remediation opens up new opportunities to enhance the speed, efficiency, and resilience of territorial recovery, making this research topic highly relevant for the contemporary scientific and practical agenda (**Fig. 3.1**).
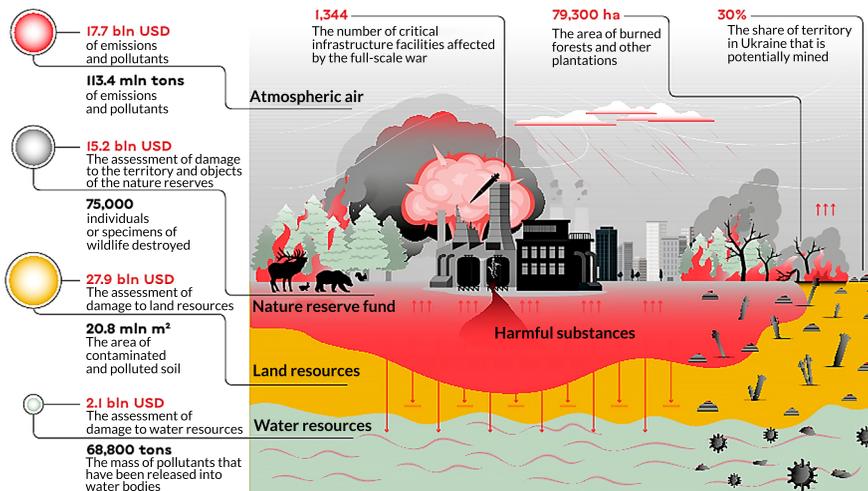

Fig. 3.1 The impact of war in Ukraine as of the end of 2024
Source: [4]

3.2 Historical, theoretical, and methodological aspects of crisis management of remediation

Key Aspects of Historical Development. It should be noted that crisis management as an independent field of governance was formed in the second half of the 20th century, when humanity faced a number of major technological disasters and military conflicts, acutely highlighting the problem of complex response to emergencies and the management of consequences elimination. Initially, efforts were concentrated on the direct liquidation of the consequences of various emergency events and

disasters (namely, locating victims, evacuating the population, clearing debris, extinguishing fires, etc., author's note), whereas environmental remediation (elimination of contaminating substances by various methods, purification of water resources, soil, air, and also waste disposal, author's note) often remained on the periphery of attention and was carried out later [5].

According to the author, traditionally in the practice of crisis management in the second half of the 20th century, the emphasis was mainly placed on organizing emergency response and ensuring the survival of the population, whereas the issues of environmental remediation were not always integrated into the general system of consequence management and often remained under the authority of separate agencies, without sufficient coordination and strategic assessment of long-term damage.

However, the accumulated experience (including, among others, the consequences of the use of defoliants in Vietnam or the environmental damage caused by the Gulf War in 1991) gradually led to the realization that environmental restoration is an integral part of post-crisis recovery (**Table 3.1**). This was also reflected in the emergence of international and national programs for assessing environmental damage and in remediation projects for affected territories.

Table 3.1 Characteristics of historical events in the context of the expanding functionality of remediation

Historical event	Objectives of remediation	Characteristics of remediation activities	Applied technologies
1	2	3	4
Chernobyl Disaster (1986)	Environmental restoration, minimizing the impact on human health	Isolation of radioactive contamination sources, large-scale decontamination of the environment	Traditional radiation protection methods, basic monitoring systems
Gulf War (1991)	Environmental restoration of marine and terrestrial ecosystems	Cleaning of oil-contaminated water bodies and soils, biodiversity restoration programs	Bioremediation, environmental monitoring, purification technologies
Wars in Yugoslavia (1990s)	Environmental restoration, elimination of consequences of armed conflicts	Demining, soil cleanup, restoration of water supply systems and infrastructure facilities	Demining, mapping of contaminated territories
Fukushima Accident (2011s)	Environmental safety, restoration of normal functioning of infrastructure	Decontamination of territories, restoration of energy and transportation infrastructure	Robotic systems, radiation monitoring, digital twins
Wars in Iraq and Afghanistan (2000s)	Environmental cleanup and restoration of life safety conditions	Removal of explosive objects, bioremediation of contaminated lands	GIS, monitoring drones, early IoT systems

Continuation of Table 3.1

1	2	3	4
Earthquake and Tsunami in Japan (2011)	Infrastructure restoration, ensuring environmental safety	Elimination of hazardous spills, restoration of dams and water supply systems, monitoring of water and soil quality	IoT sensors, early contamination detection systems, robotic cleanup
Wildfires in Australia (2019–2020)	Environmental restoration of ecosystems, prevention of erosion	Reforestation, restoration of water bodies, biodiversity monitoring	GIS, automated monitoring systems, ecosystem restoration technologies
War in Ukraine (since 2022–present)	Environmental, social, and economic restoration of affected territories; strategic strengthening of national resilience	Demining, environmental cleanup, restoration of water resources, revival of agricultural production, reconstruction of social infrastructure, digitalization of recovery monitoring	Integration of IoT, AI, extensive use of UAVs, digital twins, blockchain, intelligent recovery management systems, multi-level GIS platforms

Sources: developed by the author on the basis of data [6, 7]

As can be seen from the data presented in the table, remediation has transformed from an environmentally oriented activity focused on the purification of contaminated environments into a multifunctional recovery instrument that includes social, infrastructural, and economic aspects of rehabilitating affected areas into fully functioning territorial systems. The analysis of emergency events that have occurred since the late 20th and early 21st centuries demonstrates the fact that it can no longer be viewed in isolation from modern digital solutions. Today, its successful implementation is unthinkable without the comprehensive integration of IoT, AI, UAVs, digital twins, GIS, and blockchain technologies, which ensure systematic, coordinated, and resilient restoration of territorial socio-economic systems.

Theoretical and Methodological Foundations. Conceptually, crisis management of remediation represents an interdisciplinary field of research situated at the intersection of emergency management theory, environmental and technical sciences, information technology, and project management. Traditional crisis management models, such as the four-phase model (prevention, preparedness, response, recovery), identify remediation primarily as an element of the final phase – recovery. However, as established by the author, in modern conditions, its effectiveness directly depends on mechanisms embedded in all previous phases, including threat monitoring, rapid contamination diagnostics, risk assessment, and plan adaptation.

In addition, a key role in the theoretical foundation of modern crisis management of remediation is played by the paradigm of sustainable development and the disaster

risk reduction (DRR) concept, which aim to build safe and resilient systems in the long term. In this context, recovery must be seen as a balanced process that integrates environmental, social, economic, and infrastructural aspects – an approach that is particularly vital in post-war territorial transformation.

Additional methodological significance is provided by the theory of catastrophes, which describes the behavior of complex systems under abrupt environmental changes and serves as an important basis for forecasting crisis scenarios, particularly in technologically saturated and environmentally vulnerable zones.

Modern practice convincingly demonstrates that information technologies and digital platforms have become an integral part of the theoretical and practical toolkit for remediation. It is necessary to consider the advances of computer science, cyber-physical systems, artificial intelligence and machine learning (AI/ML), the Internet of Things (IoT), and digital modeling (digital twins), all of which establish a new level of spatiotemporal control over crisis and post-crisis processes.

Furthermore, it would be methodologically inappropriate to ignore project analysis, particularly in the context of the program-targeted approach, which is widely applied in international practice.

According to the author, the following foundational approaches serve as the methodological basis:

– the systems approach – as the foundation for building interconnections between natural, technological, and social components of the territory;

– the integrated approach – for evaluating and coordinating all elements of recovery;

– the situational approach – for adapting management decisions depending on changing conditions and uncertainty factors;

– the cybernetic approach – for analyzing feedback cycles in digital monitoring and remediation control systems.

Thus, the theoretical and methodological basis for crisis management of remediation in the 21st century is a hybrid interdisciplinary model, grounded in the principles of sustainability, digitalization, controllability, predictability, and project implementability [8].

It is also necessary to emphasize that the complexity of modern remediation tasks has necessitated the inclusion of decision-support approaches into the theoretical and methodological framework – especially under conditions of multicriteriality, uncertainty, and limited resources. A significant contribution to the scientific foundation has been the spread of multi-criteria decision analysis (MCDA) methods, which allow for structured choice among alternatives based on a set of environmental, technical, economic, and social criteria. This is particularly relevant for remediation, where one must not only achieve maximum decontamination, but also meet deadlines, remain within budget, minimize risks for implementation teams, and account for the interests of all stakeholders.

In addition to MCDA, adaptive management is actively applied – a concept originally proposed in the 1970s in ecosystem management and now reinterpreted for long-term environmental and infrastructural rehabilitation processes.

Simultaneously, the past decades have witnessed intensive development of digital theories and models of crisis management, which, in the author's view, have fundamentally transformed the methodology of remediation management itself. Theoretically, this is reflected in the concept of Digital Crisis Management, which entails the integration of digital solutions at all stages of the crisis cycle – from monitoring and forecasting to recovery and impact assessment. The first signs of digitalization emerged at the end of the 20th century with the development of geographic information systems (GIS) and satellite imagery, making it possible to map contaminated territories and model the spread of pollutants (**Fig. 3.2**).

Theoretical and Methodological Foundations of Remediation

Characteristic	Traditional Crisis Management	Modern Crisis Management	Digital Crisis Management
Focus	Recovery phase element	All phases, sustainable development	All stages of crisis cycle
Key Theories	Four-phase model	Sustainable development, DRR, catastrophe theory	Digital Crisis Management
Methodological Approaches	Project analysis	Systems, integrated, situational, cybernetic	Optimization, modeling, data governance, adaptive
Key Technologies	None explicitly mentioned	Information technologies, digital platforms	GIS, satellite imagery
Decision Support	None explicitly mentioned	Multi-criteria decision analysis (MCDA), adaptive management	Digital theories and models

Fig. 3.2 The theoretical and methodological basis
for the digitalization of crisis remediation management
Sources: developed by the author

In summary, it can be concluded that the theoretical and methodological foundation of digitalized crisis management of remediation now includes not only classical managerial concepts but also modern hybrid approaches, based on optimization algorithms, modeling, digital data governance, and adaptive strategies. All of the above contributes to the formation of a new paradigm of sustainable and technologically grounded territorial recovery, which demands in-depth scientific evaluation of the effectiveness of applied digital solutions and forecasting of their further efficient development [9].

3.3 Methodical decomposition of the study

To objectively assess the effectiveness of remediation processes in the context of the impact of digital technologies, the author proposes a methodological framework. It is based on a hybrid multi-criteria model, utilizes Monte Carlo simulation to account for uncertainties, and implements the principles of adaptive management. The main components of this methodology are presented below.

Multi-Criteria Model of Remediation Effectiveness. As a starting point, the need to account for several key aspects of the effectiveness of remediation management within a specific territorial system is emphasized: focus, locus, resources, and time. An integrated effectiveness indicator *E* is proposed as a generalized index reflecting the success of all remediation activities, aggregating the aforementioned aspects while considering their relative importance.

The formal structure of the index can be represented as follows

$$E = \sum_{i=1}^{n} \left(\alpha_i F_i^{\lambda} + \beta_i L_i^{\mu} + \Upsilon_i R_i^{\nu} + \delta_i T_i^{\xi} \right) \cdot \omega_i \cdot D, \tag{3.1}$$

where *F* – reflects the degree to which resource allocation aligns with recovery priorities ("focus"); *L* – denotes the effectiveness of the decision-making system and responsibility distribution ("locus"); *R* – reflects the efficiency of resource utilization (financial, human, material, etc.); *T* – represents temporal indicators (including the speed of implementing works related to post-conflict damage and contamination remediation).

The coefficients $\alpha, \beta, \gamma, \delta$ are weighting parameters that reflect the relative importance of each structural component in the overall effectiveness, while λ, μ, ν, ξ characterize the degree of influence that changes in the corresponding factor have on the final result.

The multiplier ω represents the composite project condition coefficient, accounting for landscape complexity, the scale and type of contamination, etc., and allows the normalization of the E index across different cases.

Finally, special attention is given to the *D* coefficient – the Digital Factor, which reflects the level of integration of digital technologies in the remediation project of the specifically analyzed territory. In other words, *D* indicates the intensity with which Digital Crisis Management (DCM) tools are used in the planning and implementation of remediation activities.

Digitalization Coefficient D. To mathematically formalize the impact of various digital technologies on the effectiveness of remediation activities, the author introduces the coefficient *D*, which is included multiplicatively in the formula for *E*, thereby increasing its value when various information-based solutions are actively applied within DCM.

The value of *D* is calculated based on which specific digital technologies are utilized and the extent of their practical contribution. Formally, it can be represented as

$$D = 1 + \sum_{j=1}^{m} \left(\omega_j T_j \cdot N \left(\mu_j, \sigma_j \right) \right), \tag{3.2}$$

where *m* – represents the number of available digital technologies used in the remediation of a specific territory; T_j – a binary indicator of the use of the *j*-th digital technology (0 – not used, 1 – used); ω_j – reflects the weight or significance of the technology for the specific remediation project; $N(\mu_j, \sigma_j)$ – the distribution function of the technology's effect, modeled as a normal distribution with expected influence μ_j and uncertainty σ_j (author's note).

Thus, if a particular technology is not applied, its contribution to *D* equals zero. However, if the digital technology is in use, its contribution is treated as a random variable reflecting the variability of its effect. The baseline value *D* = 1 corresponds to the absence of digital tools, while *D* > 1 indicates a positive digitalization impact on the overall effectiveness index *E*.

Accounting for Uncertainties Using the Monte Carlo Method. The remediation process takes place under conditions of significant uncertainty: in most cases, the outcomes may depend on weather conditions, the risk of technical failures, variations in the level and nature of contamination, as well as numerous other random factors.

To ensure the reliability of the effectiveness assessment, the author applied the Monte Carlo method in the proposed methodology. This method enables scenario analysis and allows the determination of the range of possible values for key indicators.

The Monte Carlo method, originally developed by J. von Neumann and S. Ulam in the 1940s, is based on repeatedly performing calculations with random variations in the input parameters [10].

In the context of this study, multiple iterations of the model produced a distribution of possible values of *E*, from which both the average expected remediation

effectiveness and confidence intervals can be derived. According to the author, this contributes to more substantiated managerial decision-making – rather than relying on a single deterministic estimate, a range is provided that takes into account specific conditions and overall risks [10, 11].

Thus, the use of the Monte Carlo method enables the most objective modeling of the remediation process under uncertainty and allows for analysis of the influence of various factors on the overall effectiveness of activities. This is critically important for reliable planning in crisis conditions (particularly when operating under time constraints and resource scarcity).

Adaptive Management and Dynamic Adjustment of Parameters. Another innovation in the effectiveness metric proposed by the author is the introduction of a feedback mechanism, which enables the adaptive adjustment of model parameters as new data becomes available regarding the progress of recovery activities on objects and territories.

Since the remediation process unfolds within a specific time frame, actual indicators – such as the achieved level of decontamination (F_{real}), the pace of implementation (T_{real}), the volume of resources consumed (R_{real}), etc. – may deviate from initially planned values ($F_{expected}$, $T_{expected}$, $R_{expected}$, and so on).

The methodology proposed by the author provides for the periodic recalculation of the coefficients λ, μ, ν, ξ, which are the very parameters responsible for the model's sensitivity to each structural component of effectiveness. This recalculation is carried out by computing the ratio of actual to expected values:

$$\lambda_{new} = \lambda_{old} \cdot F_{real} / F_{expected}; \tag{3.3}$$

$$\mu_{new} = \mu_{old} \cdot L_{real} / L_{expected}; \tag{3.4}$$

$$\nu_{new} = \nu_{old} \cdot R_{real} / R_{expected}; \tag{3.5}$$

$$\xi_{new} = \xi_{old} \cdot T_{real} / T_{expected}. \tag{3.6}$$

Such proportional adjustment means that if a certain component is being implemented with more difficulty than expected (for example, if the actual efficiency of resource utilization R_{real} turned out to be lower than initially planned $R_{expected}$), then the significance of this structural component (ν) automatically increases. This signals to the management personnel responsible for the remediation outcomes that greater attention must be paid to the rational use of this type of resource. Thanks to this adaptive mechanism, the remediation management model becomes more viable and

capable of adjusting to current conditions and constraints. This corresponds to the concept of Adaptive Control – dynamic management in which decisions are made at each moment based on the current situation rather than strictly following the initial plan. As envisioned by the author, this approach makes it possible to achieve a higher level of resilience of the remediation process to external changes, since the model itself will indicate where to redirect efforts and resources if the implementation of the project deviates from the original plan. Taken together, the elements described above – the multi-criteria effectiveness index with the digitalization coefficient D, scenario analysis implemented via the Monte Carlo method, and the parameter adaptation mechanism – form a comprehensive methodological construct. This can be characterized as a digital remediation management support system. In essence, the author proposes a prototype of a Digital Crisis Management System (DCMS) for post-crisis recovery, which integrates traditional methods (expert evaluation, planning) with digital technologies for modeling and analysis. The proposed approach not only allows for a one-time assessment of the effectiveness of a remediation project for a specific territory but also ensures continuous support for the post-crisis recovery process by providing management personnel at all levels of hierarchy with up-to-date information for timely response and decision-making at every stage [12].

3.4 Assessment of the role and significance of digital technologies in the remediation of affected territories

As previously noted, digital technologies exert a comprehensive influence on remediation processes – from the stages of monitoring and damage assessment to the planning and direct implementation of recovery efforts. The following section presents an analysis of key technologies (unmanned aerial vehicles, artificial intelligence, digital twins, IoT, Big Data, blockchain, etc.), evaluations of their practical application in remediation, as well as the effects achieved and the potential advantages of integrating these solutions.

Unmanned Aerial Vehicles (UAVs) in Remediation. One of the most prominent advancements in recent years has been the widespread use of unmanned aerial vehicles (drones) for environmental monitoring and restoration tasks. Drones possess a number of unique advantages, namely: they are highly mobile, capable of reaching hard-to-access or hazardous areas, rapidly collecting high-resolution data (including photo and video imagery, thermal imaging, LIDAR, etc., *author's note*), and even performing active operations (such as spraying reagents, delivering small cargo, conducting remote sensing, and more, author's note).

In the context of remediation, UAVs function as the "eyes and hands" in the localization zone of the crisis event. The practice of using drones in post-conflict and post-disaster remediation is already actively taking shape. For example, in Ukraine, a project is underway for the decontamination of agricultural land, in which specially trained experts use drones to map contaminated areas and collect soil samples [13]. Drones make it possible to promptly identify areas contaminated by shell fragments and hazardous substances, significantly accelerating the initial stage of remediation. In addition, they can be used to deliver necessary reagents and even equipment to regions that are difficult to access by ground vehicles (for example, in swamped areas or zones with destroyed infrastructure following an environmental disaster, such as after the destruction of the Kakhovka Hydroelectric Power Plant dam) [14].

Research shows that the effectiveness of UAV application largely depends on the specifics of the territory and the tasks at hand. Several main types of drones are distinguished by their functions: *Reconnaissance (mapping) drones* – used for aerial photography and subsequent mapping of damage and contamination; *Analytical drones* – equipped with special sensors for analyzing soil, water, air, and radiation levels; *Logistical (delivery) drones* – intended for transporting material resources (usually compact items, including medicines, tools, reagents, soil samples, etc., author's note); *Bioremediation drones (sprayers)* – designed to apply reagents, phytoremediation seeds, bacteria, and similar agents to designated areas. Each type of drone has its own optimal areas of application accordingly.

Artificial Intelligence and Machine Learning. As practice shows, artificial intelligence (AI) and its applied methods – machine learning (ML), neural networks, and intelligent data analysis – are becoming powerful tools for decision support in crisis management, including post-conflict remediation. AI is capable of solving tasks traditionally requiring expert involvement while automating and accelerating the process. In the context of crisis remediation management, AI developments are applied in several key areas, including:

1. *Analysis of large volumes of heterogeneous data.* Environmental assessments following a crisis generate enormous amounts of diverse data, including satellite imagery, drone-based aerial photography, IoT sensor readings, laboratory results of water and soil samples, field reports from emergency response sites, and more. Manual processing of such information is virtually impossible. In this regard, machine learning algorithms make it possible to detect hidden patterns and anomalies within the collected datasets. For example, neural networks can automatically classify types of landscape or structural damage based on imagery, and identify contamination levels through indirect indicators (such as vegetation color, processed from infrared imaging data, etc.). This significantly accelerates the creation of contamination maps and

damage assessments, while also optimizing the range of management decisions aimed at mitigating the consequences [15].

2. *Forecasting and Modeling.* It is especially important to emphasize the fact that AI models are successfully used to forecast the occurrence of emergency events themselves (for example, the globally renowned Copernicus platform), as well as to predict their consequences, including the spread of pollutants. Models trained on historical data can forecast the development of situations, complementing physical models [16].

3. *Decision Optimization.* The author's research places particular emphasis on the capabilities of AI-based optimization. Specifically, the focus is on the potential application of bio-inspired algorithms, which help solve remediation tasks under constrained conditions – for instance, selecting the most effective sequence for cleaning multiple sites, optimally allocating resources across various locations, or choosing the most efficient logistics route for delivering necessary materials.

Classical optimization algorithms (such as the Artificial Bee Colony algorithm, Ant Colony Optimization, Genetic Algorithms, Particle Swarm Optimization, etc.), when combined with simulation modeling, can propose an action plan that delivers maximum impact with minimum cost [17].

4. *Robotics and Automation.* It is also important to emphasize the role of AI, which provides the "intelligent core" of autonomous systems used in crisis management, including those applied in remediation operations. This primarily includes drone autopilots, image recognition from onboard cameras, and the action algorithms of demining robots used for neutralizing munitions, etc.

It should be noted that the more autonomous such systems are in performing dangerous operations, the lower the risk to human life and health, and the higher the speed of completed tasks. There are already examples where an onboard neural network on a drone recognizes a chemical barrel or a landmine in real-time video footage and immediately marks and transmits coordinates to a demining team [18].

5. *Digital Twins + Artificial Intelligence.* Particular attention should be paid to the role of AI in combination with digital twins and IoT: by receiving data streams from sensors, AI can diagnose deviations in real time (for example, a sharp increase in toxin concentration from a sensor may trigger a set of proposed actions, author's note), or even initiate an automatic decontamination response.

This approach brings closer to automated adaptive management, where the system responds independently to changes in the environment with minimal human intervention. This can be described as AI functioning as the "brain" of the digital remediation system for affected territories, where a designated official retains the authority to make managerial decisions. When applied correctly, this significantly enhances both the speed and validity of such decisions. Nonetheless, limitations must

also be considered: AI models require large volumes of high-quality training data, may suffer from lack of transparency (the "black box" problem of neural network decision explainability), and do not guarantee 100% accuracy. Therefore, the author considers a hybrid approach to be optimal – where AI assists humans by handling routine and computationally intensive tasks, while key decisions are made by experts using forecast data provided by AI. In the future, as successful use cases of AI in remediation accumulate, trust in these technologies will continue to grow, and in the author's opinion, they will become a standard component of crisis management [19].

GIS and Cartography. It is important to emphasize that, in practice, the creation of a digital twin begins with a high-quality cartographic foundation. Modern remote sensing tools (such as ultra-high-resolution satellites, drones with scanners, etc., author's note) play a vital role in this process, ultimately enabling the creation of detailed 3D terrain models. In this context, GIS platforms are used to further integrate various data sources. In remediation processes, GIS is often employed to assess conditions in a specific area in order to analyze the level of different risks. For example, risk maps are created to illustrate the degree of hazard in various locations (such as heatmaps of groundwater contamination spread or interactive minefield maps, *author's note*) [20, 21].

The above-mentioned remediation processes demonstrate a strong interconnection with other digital technologies, as they are "fed" by IoT data, utilize AI for rapid analysis and forecasting, are visualized through GIS, and the modeling results are used to control actual drones and machinery. This is the quintessence of digitalization – where the virtual model continuously interacts with the real world, enhancing decision-making and actual outcomes on the ground.

Internet of Things (IoT) and Sensor Networks. The author has conducted an in-depth analysis of the role and significance of the Internet of Things (IoT) in the remediation process. Essentially, it is a network of physically distributed sensors and devices interconnected with data processing centers via the Internet or other communication channels for the purpose of achieving set objectives.

In the field of remediation, IoT functions as the "nervous system" of the territory, as numerous heterogeneous sensors installed throughout the area continuously monitor environmental parameters and transmit data to the control center. Installed sensors allow for monitoring of: Water quality (including the presence of heavy metals, radioactive substances, phosphorus and nitrogen compounds, chlorine-, bromine- and fluorine-containing components, various pathogenic microorganisms, etc., *author's note*); Soil parameters (including mercury, lead, cadmium, arsenic, zinc, copper, and others, *author's note*); Air quality (such as the concentration of harmful gases, particulates, etc., *author's note*); Radiation levels, temperature, and

more. Additionally, IoT includes tracking the movement of equipment and personnel (GPS trackers), monitoring equipment status, weather stations, and even wearable sensors on personnel (to monitor the health of individuals directly involved in emergency response activities).

Big Data and Cloud Technologies. The very concept of "Big Data" is closely linked to the digitalization of crisis management related to the elimination of the consequences of emergencies and remediation, as all the aforementioned sources (drones, sensors, models, social networks, etc.) generate colossal volumes of information. The ability to collect, store, process, and analyze these data becomes critically important for achieving the set goals in the shortest possible time and with maximum possible efficiency. Cloud technologies in this regard provide virtually unlimited possibilities for storing large arrays of various types of information and accessing them from almost anywhere in the world. In the context of remediation, this means that all data related to the implementation of Ukraine's post-war recovery strategy – from high-resolution satellite images (weighing gigabytes) to the results of millions of simulations – can be stored centrally but accessed in a distributed manner.

A participant (for example, a financial donor or investor, *author's note*) can, in real time and from anywhere in the world, view the necessary project data related to remediation efforts in Ukraine without having to download all the information onto their local computer, working instead through a cloud service. This greatly facilitates collaboration among international teams, which are often involved in crisis management and disaster recovery projects. Big Data analysis involves the use of specialized methods and platforms (Hadoop, Spark, NoSQL databases, etc.) optimized for handling volumes that exceed the capabilities of conventional spreadsheets.

It should be noted that Big Data may also include social data – feedback from local residents in areas where remediation activities are being carried out, media reports, and reports from various organizations and agencies. Analyzing such data makes it possible to monitor public perception of the recovery process, respond promptly, identify bottlenecks, and assess indirect effects (for example, how quickly residents return to settlements restored after hostilities – this is also an indicator of success). Combining such social data with environmental indicators provides a more holistic picture of the recovery of affected territories.

Big Data is often accompanied by visualization tools – dashboards and interactive graphs – which help transform "raw" numbers into understandable formats for all participants in the recovery process, aimed at making more effective decisions.

Blockchain and Ensuring Data Transparency. It should be noted that although blockchain originally emerged in the context of cryptocurrency development, its unique fundamental properties – namely, decentralization, immutability of records, and

transparency – have attracted attention across a wide range of industries, including post-crisis recovery management.

According to the author's vision, in the field of remediation, blockchain can play a supporting but important role: it can ensure trust between project participants and supervisory authorities, eliminate data falsification concerning the progress and results of post-conflict destruction and contamination elimination efforts, and overall enhance the level of transparency and accountability. Smart contracts – another facet of blockchain technology – can, in the author's opinion, be applied to automate certain contractual aspects of remediation activities [22, 23].

Of course, the successful implementation of blockchain and smart contracts depends on the digital maturity of participants and the proper functioning of the relevant infrastructure. In the context of the post-war situation in Ukraine, where infrastructure has been partially destroyed, the author believes that such digital solutions can be introduced gradually, beginning with pilot projects in relatively stable regions. Nevertheless, it should be especially emphasized that international organizations financially supporting Ukraine's post-war recovery and revival are increasingly interested in the implementation of digital transparency tools to ensure that the resources they provide are used strictly for their intended purposes [24].

In conclusion, in order to confirm the relevance and significance of the research problem raised, it is appropriate to present a generalized analytical snapshot of the overall dynamics of the implementation of key digital technologies in the field of remediation and crisis management during the period from 2020 to 2025 (**Table 3.2**).

Table 3.2 Dynamics of the implementation of key digital technologies in the field of remediation and crisis management in the period from 2020 to 2025

Digital Technology	Growth dynamics and scaling forecast	Main areas of application
1	2	3
Internet of Things (IoT)	The number of connected IoT devices increased from 16.6 billion in 2023 to 18.8 billion in 2024; expected to reach 27 billion by 2025	Environmental monitoring, infrastructure management, real-time data collection
Artificial Intelligence (AI)	The global AI market reached 298.25 billion USD in 2024 and is projected to grow to 420.47 billion USD by 2025	Data analysis, forecasting, decision-making support
Unmanned Aerial Vehicles (UAVs)	The installed base of commercial drones reached 2.8 million units in 2024; expected to grow to 4.5 million by 2029	Aerial photography, material delivery, monitoring of hard-to-reach areas
Digital Twins	The global digital twin market was valued at 24.97 billion USD in 2024, with a projected CAGR of 34.2% until 2030	Process modeling, forecasting, operational optimization

Continuation of Table 3.2

1	2	3
Geographic Information Systems (GIS)	The GIS market is expected to reach 94.59 billion USD by 2025 with a CAGR of 6.38% until 2030	Mapping, spatial data analysis, route planning
Big Data	The global Big Data market is projected to reach 348.21 billion USD by 2025; growth to 924.39 billion USD is expected by 2032	Large-scale data analysis, pattern recognition, decision-making support
Blockchain	The global blockchain technology market grew from 4.19 billion USD in 2020 to 26.91 billion USD in 2024; forecast to reach 248.9 billion USD by 2029	Transparency assurance, data protection, supply chain management

Sources: developed by the author on the basis of data [22, 23, 25–29]

The data presented above clearly demonstrate the rapid development and integration of digital technologies, including in crisis and emergency management processes such as remediation. The forecast indicators underscore their importance for enhancing the efficiency of response and management, as well as for achieving resilience in the face of growing modern challenges.

3.5 Results of the testing of the methodical model for assessing the role and significance of digital technologies in remediation efficiency

The applied approaches to Digital Crisis Management (DCM) for territories affected by armed conflicts and emergency events demonstrate the urgent need to transition from traditional methods to digital hybrid crisis management systems. In this study, a comprehensive analysis of the role and significance of individual technologies was previously presented. However, recent scientific publications confirm that the isolated application of digital technologies shows a certain limitation in their effectiveness and does not provide the required level of dynamic adaptability in management.

Below are the results of the conducted analysis, which demonstrate the leading and unconditional significance of artificial intelligence (AI), as well as all types of drones (UAVs), GIS, Big Data, and machine learning (ML) in contributing to remediation efficiency (**Fig. 3.3**). During the testing of the previously proposed model for assessing the contribution of various digital technologies to the overall digitalization index of remediation process management – the D coefficient – the author relied on the concept of multi-criteria analysis and adaptive management, integrating expert evaluations, probabilistic modeling, and elements of digital monitoring.
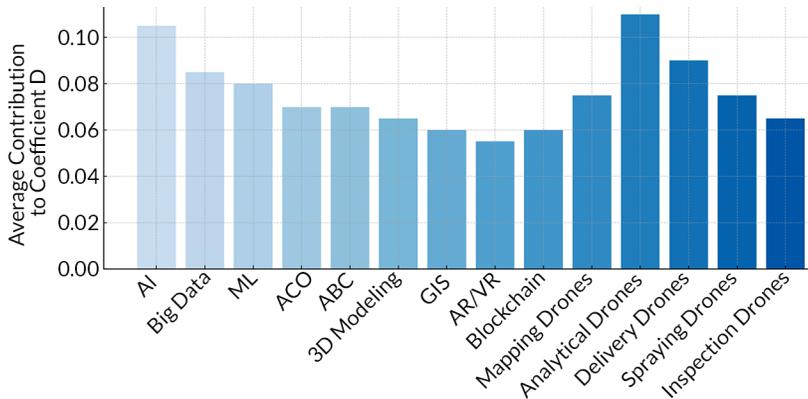
Fig. 3.3 Contribution characteristics of each technology to the overall remediation efficiency
Sources: developed by the author

In the course of modeling remediation efficiency, the author conducted a simulation of 10,000 trials aimed at assessing the distribution of the D coefficient, which reflects the integral efficiency of remediation. The use of the Monte Carlo method made it possible to account for the variability of parameters such as funding levels, weather conditions, technology failure risks, and regulatory barriers [11]. As a result of the calculations, it was found that an increase in the implementation of technologies (including UAVs) leads to a rise in the D coefficient; however, its variability also correlates with external constraints.

The author also carried out a more detailed analysis of the contribution of individual technologies to the calculation of the D coefficient. The results showed that AI ranks first in terms of impact (10.76%), followed by Big Data (7.21%), Machine Learning (8.67%), and GIS (6.3%) in fourth place. This distribution is explained by the role each of the analyzed DM (Digital Management) technologies plays in collecting primary data, continuous processing, contamination analysis, identification of optimal remediation scenarios, and route optimization. Among UAVs, the greatest contribution to the D coefficient is made by mapping drones (8.9%), followed by delivery drones (6.5%), which confirms their critically important role in monitoring and resource delivery. The least significant among all analyzed DM technologies was blockchain (4.2%), which is due to its predominantly auxiliary function in the remediation process.

Below are the results of the remediation efficiency model simulation presented as a radar chart, visualizing the potential of each DM technology across key characteristics: speed, cost, accuracy, adaptability, and transparency (**Fig. 3.4**).
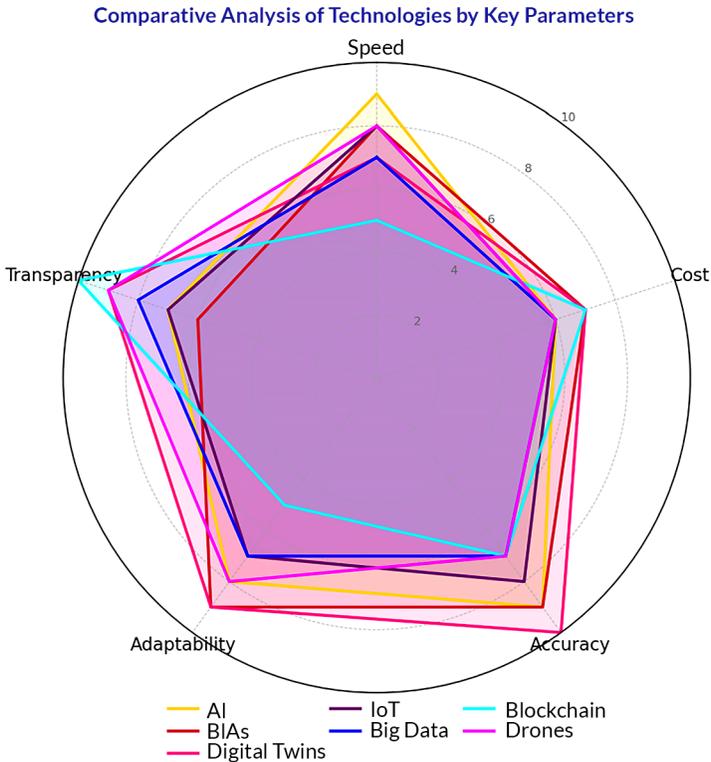
Fig. 3.4 Visual analysis of DM technologies used in remediation across key parameters
Sources: developed by the author

The presented chart clearly demonstrates both the strengths and weaknesses of each analyzed DM technology, thereby helping to identify optimal combinations for their implementation in remediation processes.

Summarizing the obtained results of modeling and analysis, it can be concluded that to ensure high recovery efficiency under conditions of time and resource constraints, the use of a single digital technology will not be sufficient. A synergistic integration of artificial intelligence, various types of UAVs, GIS, Big Data, and machine learning provides the most significant positive effect, substantially enhancing the speed, accuracy, adaptability, and transparency of post-crisis recovery processes.

The conclusions and generalizations reached by the author of this monographic study confirm the urgent need for comprehensive digitalization of crisis management

systems, where the optimal combination of digital technologies will enable the maximization of all their advantages within a unified integrated digital framework.

3.6 Conclusion

In the 21st century, remediation has transformed into something more than just the cleaning of contaminated areas and the restoration of ecosystems. Today, it plays the role of a crucial mechanism for the strategic revival of territories affected by emergency events: the restoration of the ecological environment triggers the return of people, stimulates economic development, improves the quality of life, and strengthens the international image of the country. It is remediation that can launch a multiplicative effect, which has strategic significance, including for Ukraine. The main conclusions of the study indicate that digitalization brings qualitatively new opportunities to crisis management of remediation processes and can significantly enhance their efficiency.

The conducted study has applied value through the developed methodology for assessing the effectiveness of remediation using digital technologies. The integrated model proposed by the author, which includes the calculation of the digitalization coefficient D and an adaptive mechanism for the dynamic adjustment of parameters, will enable an objective, multi-criteria assessment of the success of remediation activities under conditions of uncertainty and resource constraints. This makes the methodology particularly relevant and important for use in post-crisis scenarios where prompt and effective management decisions are required, based on the comprehensive consideration of ecological, social, and economic factors.

The developed methodology can be especially effective in the context of designing the post-war recovery program for Ukraine, allowing for the transparency and optimization of resource allocation. Thanks to the flexibility of its architecture, the methodology can be adapted to different types of emergency situations – from the consequences of armed conflicts to technological accidents and natural disasters. Thus, the model presented in the study can become an organic structural element of a modern strategy for the sustainable development of post-crisis territories.

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