CHAPTER 4

From pattern recognition to remediation management in a closed digital loop architecture for post-war logistics

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Abstract

The chapter provides an in-depth study of the problem of transition from digital diagnostics to executable management in the tasks of implementing remediation processes in areas affected by emergency events, including those of a military nature, where the effectiveness of recovery measures is largely determined by the quality of logistical coordination, the accessibility of infrastructure facilities, and the speed of managerial decision-making. Remediation in this study is interpreted as a complex, multidimensional process that includes the elimination of the consequences of war-related destruction and various kinds of contamination of soil, water, and air, the restoration of the spatial connectedness of territories, the provision of safe access, as well as the implementation of environmental, infrastructural, and socio-economic measures of post-crisis recovery. Against this background, the necessity is substantiated of transitioning from the fragmented use of digital tools to an integrated management architecture ensuring a closed cycle of "observation – recognition – geospatial diagnostics – decision – execution – verification – adaptation". As a conceptual foundation, the architecture of the Closed Digital Diagnostic Loop for Remediation Logistics is proposed, in which the Pattern Recognition block is not an autonomous analytical module, but acts as a source of diagnostic events forming inputs for geospatial integration, decision support systems, and simultaneous process orchestration. The central element of the architecture is the Decision & Orchestration Core (DSS (Decision Support System) + BPMN (Business Process Model and Notation)/CPM (Critical Path Method)) linkage, which ensures the transformation

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of the results of recognition and geospatial diagnostics into executable managerial actions in the logistics of remediation operations, including, among other things, task prioritization, resource allocation, as well as schedule planning and control of the sequence of the work being performed. Separately, the monograph reveals the role of AR/VR (Augmented Reality/Virtual Reality) and Human-in-the-Loop mechanisms as an end-to-end HMI layer, which ensure the interpretation of diagnostic results, the coordination of decisions between levels of management, as well as support for the field implementation and verification of measures.

This study has a conceptual-methodological character and is aimed at substantiating the architectural integration of observation technologies, pattern recognition, GIS (Geographic Information System), DSS, BPMN/CPM, and HMI (Human – Machine Interface) mechanisms within a unified diagnostic-managerial loop for the implementation of a complex of multidirectional tasks of post-war remediation logistics. The proposed authorial concept creates a methodological basis for the further formalization of the rules of transition from diagnostic events to managerial actions, the development of domain orchestration profiles, and subsequent scenario-based as well as empirical validation under conditions of post-crisis recovery. The monograph considers transport and logistics as the central applied profile, because it is precisely there that the diagnostics → orchestration → execution linkage is most critical, and also because they are critical subsystems through which the managerial mechanism for eliminating the consequences of emergency events and subsequent remediation is implemented. However, the concept substantiated by the authors has a broader scope of applicability, namely: the elimination of emergency events not only of a post-conflict, but also of a natural as well as technogenic nature in all spheres of the socio-economic system, and the remediation of territories as a whole.

Keywords

Pattern recognition, remediation logistics, post-war remediation, emergency situations (ES), closed digital diagnostic-managerial loop, observation systems, geographic information systems, decision support systems, BPMN, critical path method, AR/VR, Human-in-the-Loop.

4.1 Introduction

It should be noted that the unprecedented scale of destruction and the duration of military activity of a hybrid nature in Ukraine have caused systemic destruction, affected and destructively influenced not only the physical infrastructure, but also the ecological condition of territories, production chains, the socio-economic connectedness of regions and, as a consequence, the possibilities of rapid recovery. As the damage increases, it becomes obvious that post-war recovery cannot be considered exclusively as a construction and/or engineering task: it requires an integrated managerial approach capable of linking into a single whole the diagnostics of damage of various kinds, risk assessment and forecasting, the algorithmization of remediation and recovery works, their spatial, technical, and resource planning, as well as the logistical coordination and control of the execution of adopted managerial decisions.

In this context, the remediation of affected territories acquires special significance, understood by the authors as a set of measures differing in the nature of execution, aimed at eliminating the consequences of war-related destruction and contamination, restoring safe access to objects and territories, ecological stabilization, and creating conditions for socio-economic reintegration.

In the monographic study, the focus of attention is concentrated on transport and logistics; however, the conceptual idea of implementing remediation on the basis of an integrated management architecture ensuring a closed cycle of "observation – recognition – geospatial diagnostics – decision – execution – verification – adaptation" is absolutely applicable to other sectors of the national economy as well. In scientific publications devoted to the topics of humanitarian logistics and resilience, it is consistently emphasized that the effectiveness of restoration and remediation is largely determined by the quality of logistics coordination, digital integration, and the adaptability of decisions [1–4].

Thus, according to the authors' conviction, transport and logistics in this system simultaneously perform two roles at once: on the one hand, as an object of recovery (including, among other things, the necessity of reconstruction and remediation of destroyed roads, bridges, hubs, seaports and river ports, airports, railway network facilities) and, on the other hand, as an instrument for the implementation of remediation measures (in this case, this refers to the delivery of resources, the mobilization of equipment, ensuring access to intervention zones, supporting interagency coordination at all levels, etc.). It is precisely for this reason that the transport-logistics system is justifiably considered in this monograph as a critical contour of post-war recovery, on the effectiveness of which depend the speed of work execution, the safety of operations, and the attainability of the target results of remediation, reconstruction, and recovery. Along with this, one should take into account the fact that under conditions of resource scarcity, as well as the spatial heterogeneity of damage, taking into consideration their different character and the high dynamics of the situation, the key factor becomes not only the availability of data on the condition of objects and territories, but also the ability to quickly transform these data into executable managerial actions.

The relevance of such a conceptual approach is also confirmed by the scale of the losses accumulated since the beginning of the war. Thus, according to the updated joint assessments of the Ukrainian government, the World Bank, the European Commission, and the UN (RDNA), the total cost of the recovery and reconstruction of Ukraine continues to grow: the estimate amounting to 486 billion USD in RDNA3 (as of the end of 2023) was increased to 524 billion USD in RDNA4 (as of the end of 2024), and in the update published on February 23, 2026 (RDNA5, covering the period up to December 2025), the aggregate needs for remediation, reconstruction, and recovery are already estimated at approximately 588 billion USD, while direct damage exceeds 195 billion USD. Among the most affected sectors are the housing sector, transport, and energy [5–9]. All of the above-listed data indicate that post-war recovery cannot be built on point-based, fragmented solutions; the foundation of such recovery must be an architecturally organized digital management loop that will make it possible to ensure prioritization and adaptive reallocation of resources under conditions of an updated situation.

Despite the active development of digital tools for monitoring, damage mapping, and decision support, in the practice of eliminating the consequences of emergencies and post-crisis remediation, a substantial gap remains between the stages of observation, diagnostics, and the execution of managerial decisions. Observation systems (including UAVs (Unmanned Aerial Vehicle), satellite data, thermal and multispectral imaging) are capable of ensuring the operational collection of information; however, by themselves they do not form managerial actions. Methods of pattern recognition and intelligent analytics make it possible to identify damage, risk zones, and changes of condition, but their results often remain at the level of cartographic or reporting interpretation [10, 11]. GIS and DSS strengthen the spatial and analytical component; however, without formalized process orchestration and mechanisms for execution control, they do not ensure the completeness of the managerial cycle. As a result, the managerial loop proves to be broken, while the speed and quality of decisions are reduced precisely under those conditions where the cost of error and delay is maximally high.

In the present study, a conceptual-methodological solution to the indicated problem is proposed on the basis of the architecture of a closed digital diagnostic-managerial loop for the remediation logistics of post-war recovery. The key idea consists in the transition from pattern recognition to remediation management through a formalized mechanism for translating diagnostic events into executable tasks, scenarios, and processes. In contrast to approaches in which the Pattern Recognition block is considered as an autonomous analytical module, in this work it is conceptualized as a source of diagnostic events and confidence/uncertainty assessments, integrated into the geospatial layer and further transformed into managerial actions.

The main element of the proposed architecture is the Decision & Orchestration Core (DSS + BPMN/CPM), ensuring the prioritization of remediation tasks, the planning of resources and timeframes, the formalization of the sequence of operations, and execution control under conditions of a changing situation. Such a core makes it possible to connect digital diagnostics with the process implementation of decisions, thereby forming an executable managerial loop rather than a set of disparate digital tools. Additionally, the study expands the role of AR/VR and Human-in-the-Loop mechanisms, which are considered not as auxiliary visualization, but as an end-to-end HMI layer of interpretation, coordination, field support, and verification of decisions at all phases of the loop.

It should be emphasized that the proposed architecture has a broader horizon of applicability and may be used for the tasks of eliminating the consequences of emergency situations of a natural, technogenic, and military nature, as well as for the post-crisis remediation of territories in various domains. At the same time, in this work the transport-logistics sphere is considered as the priority implementation profile, since it is precisely in it that the necessity of a rapid and reliable transition from diagnostic data to managerial action is manifested most clearly [12]. This makes it possible simultaneously to preserve the interdisciplinary scale of the concept and to ensure its subject-specific focus on tasks of high practical significance.

The purpose of the study is to substantiate and structure the concept of the Closed Digital Diagnostic Loop for Remediation Logistics, in which the results of observation and pattern recognition are transformed into executable managerial decisions through the integration of GIS, DSS, BPMN/CPM, and an end-to-end HMI layer. Within the framework of this purpose, emphasis is placed on the architectural integrity of the loop, the logic of the transition from diagnostics to process orchestration, as well as on determining the directions and prospects of practical application [13, 14].

To achieve the stated purpose, the following tasks are solved in the work: clarification of the subject field of research at the intersection of the elimination of the consequences of emergency situations (of a natural, technogenic, and military nature), post-crisis recovery, and remediation logistics, with substantiation of the transport-logistics sphere as the priority domain for implementation of the concept; substantiation of the necessity for and development of the conceptual architecture of a closed digital diagnostic-managerial loop (Closed Digital Diagnostic Loop) for post-war remediation logistics, including interrelated functional blocks of observation, recognition, geospatial integration, decision orchestration, execution monitoring, and feedback; determination of the role of the Pattern Recognition block and geospatial diagnostics as a source of diagnostic events (including confidence/uncertainty assessments) forming inputs for the managerial core and ensuring the transition from data analysis to decision-making; disclosure of the role of AR/VR and Human-in-the-Loop mechanisms as an end-to-end HMI layer and determination of the prospects for scaling the proposed architecture to a wider range of tasks of eliminating the consequences of emergency situations and the remediation of territories, including the formation of domain profiles for further research [14].

4.2 Degree of study of the problem and research gaps in the field of digital diagnostics and management of remediation logistics

First of all, it should be noted that the problematics of digital management of the elimination of the consequences of emergency situations (ES) and post-crisis recovery have been developing rapidly in recent years; however, predominantly along separate directions: process management, geographic information systems, artificial intelligence, decision support systems, platform-based data integration, and visualization. The scientific exploration by the authors of the problematics under study revealed the following. Thus, such aspects as the following are covered in open sources quite deeply and broadly:

– the use of remote sensing, satellite data/UAV for crisis monitoring and damage mapping. For the tasks of recognition/segmentation/classification in the post-disaster environment, there already exist high-quality datasets and an established scientific base. In particular, RescueNet offers high-resolution UAV images with annotations for classification and semantic segmentation, specifically oriented toward damage assessment after disasters [15]. This constitutes a weighty argument in favor of the fact that the transition to pattern recognition proposed in this study is not an artificial "expansion of the topic", but relies on the already established empirical and methodological base of CV/remote sensing for crisis tasks;

– the application of deep learning/pattern recognition for the purposes of detection, segmentation, damage assessment, and change detection in the disaster context;

– the use of AI in disaster management. Contemporary reviews show that AI is applied for forecasting, risk assessment, evacuation planning, resource allocation, and big data analysis, but also emphasize the problems of trustworthiness, bias, explainability, and integration into real decision-making loops [16]. This creates a strong foundation for the Pattern Recognition & Diagnostic Analytics block in your architecture, but simultaneously indicates the necessity of a separate mechanism for transforming recognized patterns into managerial actions;

– the application of GIS/Web-GIS platforms as a basis for integrating observations and modeling for the purpose of making effective decisions. Thus, a separate cluster of studies on GIS and WebGIS in risk and emergency management is well developed. For example, the RiverCure Portal demonstrates that a Web-GIS platform can combine observations, modeling, the work of different organizations, and decision support at various stages of the risk management cycle (preparedness, operational response, risk assessment), including data assimilation and a multi-stakeholder configuration [17]. This is especially valuable for our concept, because geospatial integration in it must perform not a decorative, but a diagnostic-operational function (risk layers, accessibility, constraints);

– the advantages of BPMN and workflow approaches for formalizing emergency/disaster response processes [18]. Thus, in the works of Betke and co-authors, methodological extensions of BPMN for disaster response processes are discussed, which confirms the scientific viability of process modeling in the crisis sphere;

– the features of adaptive workflow execution in emergency response (including for run-time reconfiguration, execution engines);

– CPM in individual tasks of crisis management, including the elimination of the consequences of emergency situations, as well as the planning of remediation operations and emergency logistics. Thus, CPM has long been established in project management as a tool for identifying the critical sequence of works, task dependencies, and schedule control. In modern interpretations, its role as a communication and management tool for complex projects, and not only a computational mechanism, is emphasized [19]. For remediation logistics, this is directly relevant, since time delays at critical nodes (routes, access to facilities, infrastructure recovery) rapidly scale risks and cost;

– the application of integrated platforms (BIM/GIS/IoT/monitoring) and visualization in humanitarian logistics and crisis management for situational awareness and support of managerial decisions. Contemporary platform solutions already demonstrate the value of integrating GIS, BIM, and real-time monitoring for multi-hazard response and post-disaster recovery. Thus, for example, in the work of C. Hong et al., an open platform with GIS/BIM integration, real-time monitoring, visualization, and even a VR component for training/experience functions was investigated. This confirms the practical feasibility of a multilayer digital architecture as a whole [20].

Separately, it should be noted that, in the remediation direction, a significant body of scientific research is presented (including that of the authors of this monograph), which is devoted to contaminated sites, brownfields, and the selection of cleanup/recovery technologies, including DSS and MCDA (Multi-Criteria Decision Analysis) approaches [21]. At the same time, reviews on DSS for brownfield/contaminated land management emphasize the importance of integrating disciplines and supporting complex decisions, but, as a rule, do not proceed to the process orchestration of large-scale post-conflict logistical operations. It is precisely in this that the subject shift in contemporary research consists, namely, the comprehensive transdisciplinary study of the problematics of remediation + logistics + post-war recovery + digital orchestration.

Thus, the problematics of digital management of the elimination of the consequences of emergency situations (ES) and post-crisis recovery have been developing rapidly in recent years; however, predominantly along separate directions: process management, geographic information systems, artificial intelligence, decision support systems, platform-based data integration, and visualization.

Along with this, the authors of the monograph established the fact that much less frequently mentioned in publications is a unified architecture applied (or proposed for use), where:

– pattern recognition forms diagnostic events with confidence/uncertainty;
– while they would be translated into GIS layers;
– then into executable managerial actions through DSS + BPMN/CPM;
– with an execution and feedback loop;
– and with an end-to-end HMI layer of AR/VR + Human-in-the-Loop.

According to the vision of the authors of this study, the hypothesis that precisely such a linkage for remediation logistics (especially in the post-war context) appears reasonably relevant and may be positioned as an architectural-methodological novelty.

In contrast to works considering pattern recognition, GIS platforms, workflow modeling, and AR/VR support predominantly as separate or weakly connected tools, this study proposes an integrated architecture of a closed digital diagnostic-managerial loop of remediation logistics. In it, the results of Pattern Recognition and geospatial diagnostics are formalized in the form of diagnostic events and, through the Decision & Orchestration Core (DSS + BPMN/CPM), are transformed into executable managerial actions with a verification loop and adaptive feedback, under end-to-end support of AR/VR and Human-in-the-Loop mechanisms.

Based on the analysis of the literature, the following research gaps can be identified:

– *the architectural gap*, which is manifested in the absence of a sufficiently clearly formalized concept of a closed digital diagnostic-managerial loop that organically unites surveillance → pattern recognition → geospatial integration → orchestration core → execution monitoring → feedback learning into a unified logical system for remediation logistics;

– *the operational gap*, characterized by the fact that in most studies the mechanism for transforming recognition results (namely: detection/segmentation/classification/change detection) into executable managerial actions is insufficiently disclosed, taking into account the priorities of remediation tasks, the timeframes of their execution, the availability of necessary resources, and interagency coordination;

– *the interface gap (HMI gap)*. Thus, AR/VR and Human-in-the-Loop mechanisms are rarely described as an end-to-end layer that ensures the interpretation, coordination, and verification of decisions between analytics, management, and field execution;

– *the domain-applied gap.* Thus, it should be recognized that there exists a deficit of publications in which the logic of process orchestration (BPMN/CPM) and digital diagnostics is systemically adapted precisely to post-war remediation logistics, and not only to natural disasters, industrial facilities, or individual contaminated sites.

4.3 Materials and methods of the study

The authors emphasize that the present study has a conceptual-methodological character and is aimed at developing the architecture of a closed digital diagnostic-managerial loop for post-war remediation logistics, rather than at the empirical validation of a specific software prototype.

The methodological basis of the study was formed on the basis of systemic, comprehensive, and integrative approaches. The systemic approach in the monograph was used for the in-depth study of remediation logistics as a multicomponent managerial system, including observation, diagnostics, geospatial interpretation, decision-making, execution, verification, and feedback. In the context of the problematics under study, the comprehensive approach allowed to take into account the interdisciplinary character of the subject field, uniting the tasks of eliminating the consequences of emergency situations, including the post-war recovery of territories (as is the case with Ukraine), transport-logistical support, and digital management. The integrative approach was applied by the authors' collective of this monographic study for the synthesis of heterogeneous technological and methodological components into a unified architectural framework oriented toward the transition from digital diagnostics to executable managerial actions.

As the basic analytical method, an analysis of the degree of study of the problem and a comparative analysis of publications in the following directions were used: surveillance systems, pattern recognition, GIS/DSS, process/workflow orchestration, BPMN, CPM, AR/VR, and Human-in-the-Loop in the context of emergency situations, post-disaster recovery, and remediation. On the basis of the conducted analysis, the identification of research gaps between the existing solutions in the field of digital diagnostics and the tasks of process-managerial implementation of adopted managerial decisions was carried out. The results of the literature analysis served as the basis for formulating the research hypothesis about the necessity of a closed digital diagnostic-managerial loop as an integrated architecture for the management of remediation logistics.

The key method of concept construction was architectural-conceptual modeling, which was focused on the formalization of the structure and logic of interaction of the functional blocks of the system. At this stage of the study, the authors of the monograph used the functional decomposition of the initial extended structure with the subsequent optimization of interconnected macro-blocks: collection of observation data, recognition and diagnostic analytics, geospatial integration, decision-making and orchestration core, execution monitoring and verification, feedback, and adaptive refinement. The authors made an attempt, with the help of decomposition analysis, to optimize as much as possible and, along with this, to reduce structural redundancy, as well as to increase the conceptual clarity of the architecture without loss of substantive completeness.

For the formalization of the managerial component, the authors' collective used a process-oriented approach relying on Business Process Model and Notation (BPMN) as a tool for structuring, orchestration, and control of the sequence of actions in remediation logistics. BPMN in the study is considered not only as a language of visual description of processes, but also as a basis for building the executable logic of interaction of all participants at different levels of the management system, the algorithm for task execution, and the determination of control points. In addition to this, the critical path method (CPM) was applied for the purpose of conceptualizing the temporal structure of works, dependencies between the performed tasks, critical nodes, and constraints in terms of established deadlines and actually available resources under conditions of the prevailing scarcity of post-war recovery.

Methods of geospatial integration (GIS) and decision support systems (DSS) were also included in the research framework as tools for the operationalization of recognition results in the management space. Within the framework of conceptual modeling, GIS was used for the representation of georeferenced diagnostic events, risk zones, access constraints, as well as the identification of damage layers and routing parameters. DSS was applied by the authors as a mechanism of multicriteria prioritization and selection of managerial alternatives, taking into account resource scarcity, temporal constraints, and the constantly changing situation. Artificial intelligence (AI) technologies, including pattern recognition, are considered in this monograph as a source of diagnostic events and confidence/uncertainty assessments, which are necessary for launching and adapting the managerial loop.

A separate methodological significance is held by the conceptualization of AR/VR and Human-in-the-Loop mechanisms as an end-to-end HMI layer. For this purpose, the monograph used the approach of functional mapping of the roles of AR/VR/HITL across the phases of the loop, namely: interpretation of diagnostics, coordination of decisions, support of execution, verification, and learning (**Fig. 4.1**). As a result, this made it possible to avoid their reduction to exclusively visualization means and instruments. Ultimately, such an approach ensured a more rigorous integration of human-machine interaction into the management architecture and strengthened the substantiation of the scientific novelty proposed in the monograph.

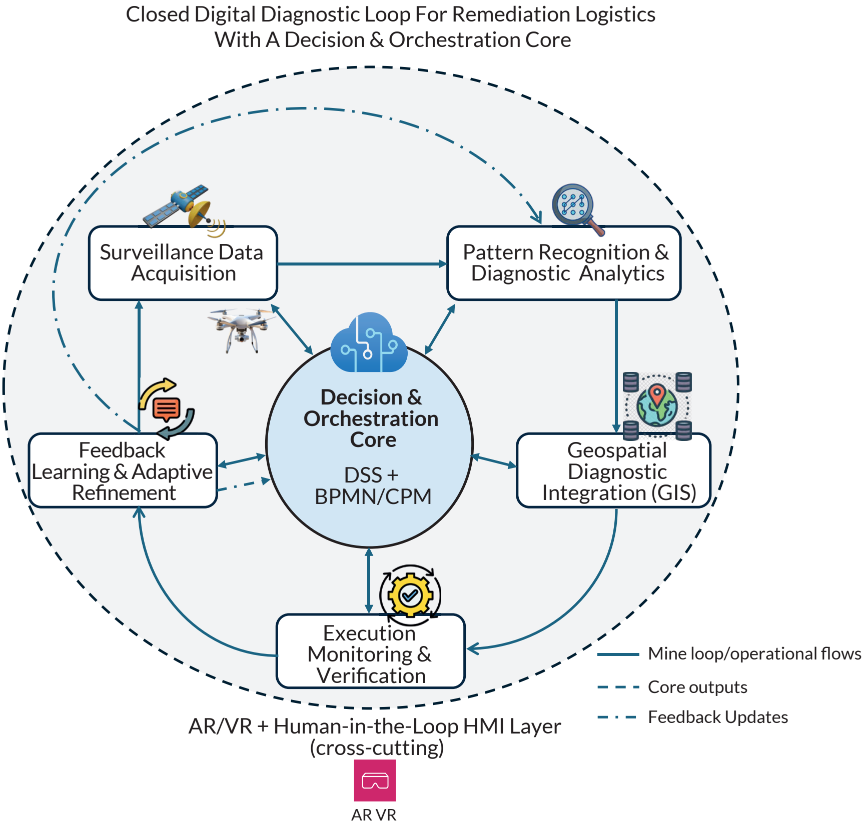

Fig. 4.1 Closed digital diagnostic loop for remediation logistics with a Decision & Orchestration Core

In addition to the above-described methodological techniques, the method of logical synthesis was also applied for the purpose of constructing the transition from diagnostic events to executable managerial actions (the diagnostics-to-action logic) within the framework of the Decision & Orchestration Core (DSS + BPMN/CPM). On this basis, a conceptual model of a closed digital diagnostic-managerial loop for post-war remediation logistics was formed, with the identification of a dual-loop core and domain-specific profiles of further development.

Thus, the totality of the materials and methods used in the monograph provides a sufficient methodological basis for substantiating the proposed architecture and formulating the tasks of its subsequent scenario-based and empirical validation in the authors' further studies.

4.4 Conceptual architecture of the closed digital diagnostic-managerial loop

First of all, it should be noted that this study is a continuation of the in-depth study published earlier, namely on APRe-TISRM, in which the authors proposed [21]:

– the S&D → BIM/DT → 4D/5D + BPMN → execution → post-monitoring loop;
– the role of Surveillance & Diagnostics;
– pattern/image recognition;
– Human-in-the-Loop;
– gates (Confidence/Eco/Safety/Audit);
– the translation of observation/recognition results into manageable actions.

That is, the authors fundamentally laid down: the diagnostic input, the semantic core, the orchestration of processes, as well as the execution and feedback loop. This study makes the next step, namely: it conceptualizes the closed digital diagnostic-managerial loop, strengthens the role of Pattern Recognition as part of the architecture, and introduces AR/VR as a cross-cutting HMI layer. Thus, this is a deepening of the architectural decomposition. It is very important to emphasize that BIM/DT and AR/VR in the logic of the study are not mutually exclusive technologies, but orthogonal and complementary ones. Thus, BIM/DT is responsible for semantic/operational state representation, and AR/VR is responsible for human-centered decision interaction and execution support.

One of the key tasks of the authors is the reflection of a logical scientific evolution:

1. *Stage* 1 *(BIM/DT-oriented remediation):* creation of the semantic-operational architecture of APRe-TISRM, metrics, interoperability, BOR-index, the S&D → → BIM/DT → Ops linkage.

2. *Stage* 2 (*Pattern recognition* → *remediation management in closed loop):*

– expansion to a closed diagnostic-managerial loop with the explicit identification of:

a) PR analytics block;
b) geospatial diagnostic integration;
c) Decision & Orchestration Core;
d) execution monitoring;
e) feedback learning;
f) AR/VR + HITL HMI layer (**Fig. 4.2**).

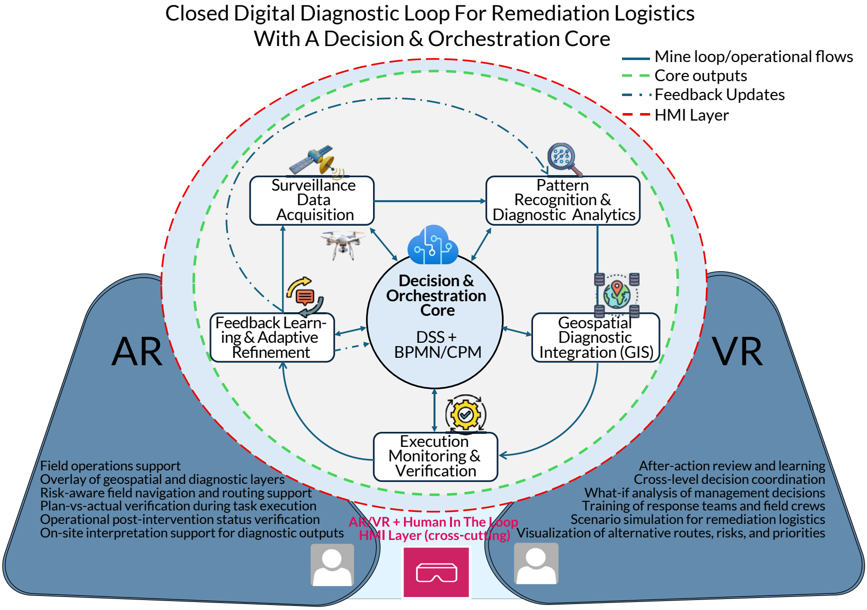

Fig. 4.2 Conceptual model of the closed digital diagnostic-managerial loop for remediation logistics: from pattern recognition to the orchestration and execution of decisions

It is absolutely logical that, as a result, an expansion of the research horizon occurred, a shift of emphasis from the object-semantic and interoperable architecture (BIM/DT) to the human-machine and process-orchestration layer (AR/VR + + HITL + DSS/BPMN/CPM), while preserving BIM/DT as an important element of the integrated architecture.

It is fundamentally important to note that this study does not cancel the BIM/DT-oriented model, but develops it in the direction of adaptive architectural reconfigurability and expands the functional loop through the HMI layer (AR/VR + HITL), ensuring cognitive and operational connectedness.

For greater understanding of the scientific position of the authors, it is proposed a decomposition of the general architecture with the identification of a dual-loop core:

1. *Loop* 1 *(semantic-operational)* is responsible for:

– representation of the state of objects/territories;
– geospatial referencing;
– traceability of state and changes;
– coordination of digital entities and field observations.

2. *Loop* 2 *(decision orchestration)* is responsible for:

– prioritization;
– planning of resources/timeframes;
– formation of executable tasks;
– workflow management and execution control.

It is precisely the dual-loop core that best explains reconfigurability:

– recognition algorithms can be changed without breaking the traceability loop;

– the orchestration logic (BPMN/CPM/DSS) can be changed without breaking the BIM/DT/GIS state model;

– the HMI (AR/VR/HITL) can be strengthened without changing the fundamental data semantics;

– components can be switched on/off depending on the type of emergency situation and the phase of works.

That is, reconfigurability becomes a formally substantiated property. Within the framework of the study, reconfigurability is considered as a systemic property of the loop, ensuring the controlled restructuring of diagnostic, geospatial, orchestration, and HMI components without loss of the integrity of the logic of decision-making and execution.

For the purpose of clarifying the boundaries of applicability of the architecture, it is expedient to distinguish three modes of its configuration:

– BIM/DT-centric mode (for the management of individual infrastructure objects, where the semantic-operational layer dominates);

– loop-centric orchestration mode (for territorial multi-actor remediation logistics, where the central role is played by the DSS + BPMN/CPM core);

– hybrid mode (BIM/DT + loop + AR/VR/HITL) for complex post-crisis and post-war scenarios (**Fig. 4.3**).

Such differentiation confirms that differences in technological emphases reflect not a contradiction of approaches, but a manifestation of the adaptive architectural reconfigurability of a unified diagnostic-managerial loop.

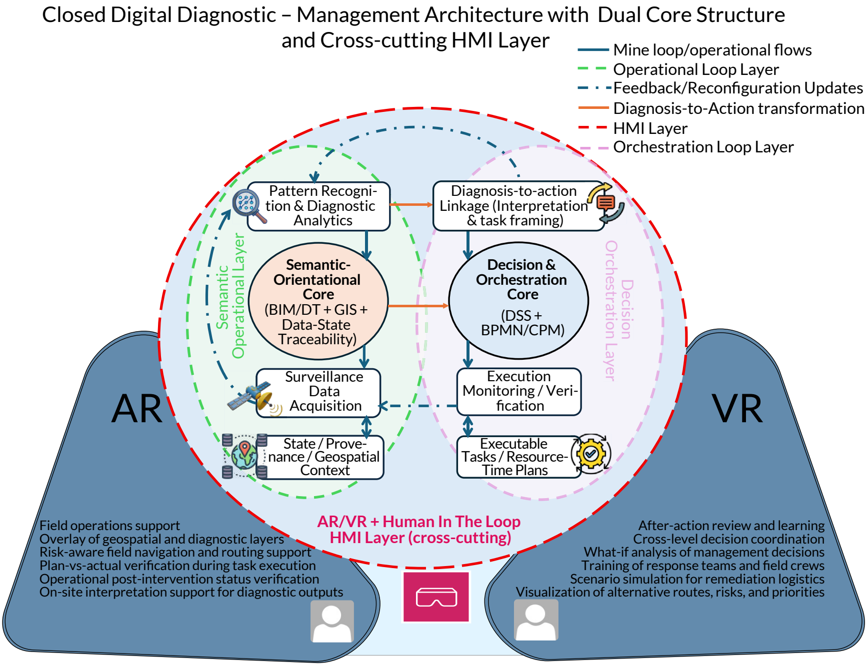

Fig. 4.3 Dual-core architecture of the closed digital diagnostic-managerial loop for remediation logistics: semantic-operational core, orchestration core, and cross-cutting HMI layer

The representation of the extended architecture in the form of a formalized model with a dual-loop nature of the core is logical and methodologically expedient, since it makes it possible to eliminate the contradiction concerning the relationship between BIM/DT, GIS, data-state traceability, and the decision orchestration core (DSS + BPMN/CPM). Such an approach demonstrates that the indicated components do not compete with each other, but form functionally distinguishable, yet interrelated levels of a unified system: the semantic-operational layer ensures state representation, geospatial referencing, and the traceability of changes, whereas the decision orchestration core transforms diagnostic results into executable actions taking into account timeframes, resources, and workflow constraints. In this architecture, AR/VR + Human-in-the-Loop mechanisms are naturally interpreted as a cross-cutting HMI layer ensuring cognitive and operational connectedness between diagnostics, management, and execution. Formalization in such a formulation also strengthens the substantiation of the property of adaptive architectural reconfigurability, making it possible to describe the change in the configuration of the loop depending on the type of emergency situation, the recovery stage, and the quality of available data.

Summarizing all of the above-presented, it should be noted that the previous and the present studies may be presented as consecutive stages in the development of a unified concept of digital management of the elimination of the consequences of emergency situations and the remediation of territories, where the first work lays the BIM/DT-oriented foundation of reengineering and traceability, and the second one (that is, the present study) expands the architecture to a closed diagnostic-managerial loop with an emphasis on pattern recognition, orchestration, and human-centered execution support.

From a qualitative perspective, the proposed approach differs in that it integrates previously fragmented components (Pattern Recognition, GIS, DSS, BPMN/CPM, as well as AR/VR and Human-in-the-Loop mechanisms) into a unified closed management architecture. The proposed dual-core model, combining the semantic-operational layer and the decision and orchestration core, ensures structural flexibility and allows adaptive reconfiguration of the system without compromising its integrity. At the same time, the cross-cutting HMI layer enhances cognitive, coordination, and operational connectedness between the stages of diagnostics, decision-making, and execution. As a result, the approach enables not only data analysis but also its consistent transformation into executable and verifiable managerial actions, which fundamentally distinguishes the proposed architecture from fragmented digital solutions.

4.5 Metric representation of the closed loop and measurement of the synergy of the dual-loop core

After substantiating the conceptual architecture of the closed digital diagnostic-managerial loop, there arises a necessity to move from structural description to the presentation of its measurable effects and mechanisms of practical implementability. For this purpose, the authors introduce a metric representation of the "diagnosis-to-action-to-verification" cycle and indicators that will make it possible to quantitatively capture the degree of closure of the loop, as well as the synergy of the dual-loop core through traceability closure. Such an evaluative framework makes it possible to set criteria by which the managerial effectiveness of the integration of the semantic-operational layer and the decision orchestration core may be interpreted, moreover, in different configuration modes.

The authors of the study decided to form a step-by-step metric scheme coordinated with the structure of the loop and its dual-loop core (**Table 4.1**).

At the first stage, the recognition system forms a flow of diagnostic events on the basis of observation data and simultaneously evaluates the degree of their reliability. This makes it possible to create the initial informational basis for making subsequent managerial decisions. At the second stage, diagnostic events are transformed into specific executable tasks, each of which receives resource, temporal, and process formalization and constraint. In other words, a transition takes place from the identification of a problem to the formation of an optimal action plan. At the third stage, control and confirmation of the actual implementation of the tasks set earlier are carried out. However, it should be especially emphasized that, for the full closure of the managerial cycle, it is not sufficient merely to confirm their execution. Along with this, it is also necessary to record the proven change in the state of objects, territories, or affected sites in the semantic-operational environment. It is precisely this stage that completes the full cycle "diagnostics – action – verification – state updating" and makes management truly closed.

It is fundamentally important that such a result is possible only through the joint operation of the two parts of the architecture. In the proposed configuration, the first is responsible for translating diagnostic data into managerial actions, while the second is responsible for the recording, updating, and traceability of the state after the execution of the complex of remediation works. Therefore, synergy is manifested not simply in the execution of a set of tasks differing in character, but in the ability of the system to bring diagnostic events to a confirmed and traceable result. In this context, it should be emphasized that, in order to assess the effect of such integration, it will be expedient to compare different modes of operation of the architecture, namely: with the predominance of the semantic-operational loop, with the predominance of the decision orchestration loop, as well as in a hybrid configuration. The synergistic effect will be considered achieved only in the case when the joint operation of the two loops ensures a more complete and evidentiary completion of the managerial cycle, in comparison with the operation of each of them separately. This approach makes it possible to connect the conceptual architecture directly with the practical assessment of its operation and creates a basis for further empirical and simulation-based verification in the tasks of remediation and post-crisis recovery (and not only in the transport-logistics sphere).

Table 4.1 Step-by-step metric representation of the closed loop and measurement of the synergy of the dual-loop core

No.	Loop step (structural)	Formalized object/set	Metric/calculated Indicator	Functional meaning/application
1	2	3	4	5
1	PR generates diagnostic events and uncertainty	D_T, (N_{*diag*}=	Let R_T – be the initial flow of "raw" diagnostic triggers from Pattern Recognition/Digital Diagnostics over period T (detections, segmentations, change detection, etc.). Each trigger $r \in R_T$ has a minimal set of attributes $r = <t, g, c, p, u, s>$, where t – time (timestamp); g – geolocation (specific place/polygon/object); c – class/type of event (damage/contamination/blockage/change, etc.); $p \in [0,1]$ – confidence; $u \in [0,1]$ – uncertainty; $s \geq 0$ – severity/impact score (importance/severity; may be from model, DSS, or rules). It is expedient to introduce a rule of "managerial significance" $D_T = \left\{ \begin{matrix} r \in R_T \mid p(r) \geq \tau_p \wedge u(r) \leq \\ \tau_u \wedge s(r) \geq \tau_s \end{matrix} \right\}$, where τ_p, τ_u, τ_s – thresholds (may be fixed or reconfigurable by modes)	Pattern Recognition/Digital Diagnostics forms events d_i with attributes: t, g, type, conf/unc
2	Core transforms events into tasks	A_T, (N_{*act*}=	Let A_T – be the set of executable remediation-workflow tasks created by the decision orchestration core (DSS + BPMN/CPM) over period T as a managerial response to diagnostic events. Each task $a \in A_T$ is described by the minimal attribute set $a = <id, t_c, g, \theta, \pi, k, \rho, \sigma>$, where id – task identifier; t_c – creation timestamp; g – geolocation/object (site/asset); θ – task type (inspection/clearance/repair/remediation/logistics delivery/etc.); π – priority; k – criticality/risk; ρ – resource requirements (skills/equipment/materials); σ – status (created/assigned/in-progress/completed/verified/rejected). Optimized metric N_{act}: $N_{act} = \left\| A_T^{diag} \right\|$, $A_T^{diag} = \left\{ a \in A_T \mid \exists d \in D_T^* : a \in f(d) \right\}$	Decision & Orchestration Core (DSS + BPMN/CPM) applies prioritization rules as well as orchestration and creates workflow tasks

Continuation of table 4.1

1	2	3	4	5
3	Execution monitoring confirms completion	V_T, (N_{ver}=	Verified tasks (confirmed execution) $V_T = \{a \in A_T^{diag} \mid veryfy(a) = 1\}$. Number of verified tasks $N_{ver} = \lvert V_T \rvert$. Verification ratio $VR = \frac{N_{ver}}{N_{act}}$ or $VR = \frac{\lvert V_T \rvert}{\lvert A_T^{diag} \rvert}$	Execution Monitoring/Verification records the fact of the implementation of remediation tasks and their compliance with requirements
4	SO-layer records state updates	T_T, (N_{tr}=	Traceability state updates (as-is → as-done/as-remediated) $T_T = \{a \in V_T \mid trace\_update(a) = 1\}$. Number of confirmed traceability updates $N_{tr} = \lvert T_T \rvert$	Semantic-Operational layer (BIM/DT + GIS + traceability) records the update "as-is → → as-done/as-remediated" (evidentiary traceability)
5	Assessment of closure quality via traceability	TR	Traceability ratio $TR = \frac{N_{tr}}{N_{ver}}$	Shows maturity of integration: how many verified works result in evidentiary state updates (audit, reporting, quality management)
6	Interpretation of dual-core synergy	–	Metric representation of synergy via $D2A_I^{(tr)}$ and TR: $D2A_I^{(tr)} = \frac{N_{tr}}{N_{diag}} = \frac{\lvert T_T \rvert}{\lvert D_T \rvert}$ and $TR = \frac{N_{tr}}{N_{ver}} = \frac{\lvert T_T \rvert}{\lvert V_T \rvert}$	The indicators capture the share of diagnostic events that ended with an evidentiary state update (traceability), and the share of verified works anchored in the semantic-operational loop. Therefore, it is precisely they that are the most direct metrics of the synergy of the dual-loop core
7	Mode-based comparison (SO/DO/Hybrid)	$D2A_I^{(tr)}(SO)$, $D2A_I^{(tr)}(DO)$, $D2A_I^{(tr)}(Hybrid)$	Synergistic increment $\Delta_{syn} = D2A_I^{(tr)}(Hybrid) - \max\{D2A_I^{(tr)}(SO), D2A_I^{(tr)}(DO)\}$	Shows measurable "added" integration effect: hybrid mode provides more complete traceability closure compared to dominance of a single loop

From a quantitative perspective, the proposed architecture introduces a metric framework that enables the evaluation of not individual analytical stages, but the full cycle "diagnosis – decision – execution – verification – state update". In particular, it allows measuring the proportion of diagnostic events transformed into executable managerial actions, successfully verified, and completed with evidence-based and traceable state updates. This makes it possible to quantitatively identify gaps between analytics, orchestration, and execution, as well as to provide a basis for comparing different architectural configurations and evaluating the synergistic effect of their integration.

4.6 Expansion of the role of AR/VR and Human-in-the-Loop mechanisms in the architecture of the closed digital diagnostic-managerial loop

Within the framework of the proposed concept of a closed digital diagnostic-managerial loop, it is expedient to reconsider the traditional role of AR/VR technologies and Human-in-the-Loop (HITL) mechanisms, shifting the emphasis from their auxiliary visualization function, which is traditionally highlighted in the scientific literature, to a systemically significant level of the human-machine interface (HMI-layer). Thus, in the predominant majority of applied solutions, AR/VR are used mainly as means of representing the actual situation in cases of personnel training or demonstration of scenario development; however, under conditions of eliminating the consequences of emergency situations and implementing remediation measures, such an approach is insufficiently studied and covered. This is due to the fact that the key problem of modern practice lies not only in the lack of data, but also in the gap between digital diagnostics, managerial interpretation, and the execution of planned decisions in field conditions. In this regard, AR/VR and HITL, according to the authors of the monograph, should be considered as a cross-cutting layer that will ensure the cognitive connectedness of the loop "observation – recognition – geospatial diagnostics – decision – execution – verification – adaptation". The expansion of the functional role horizon as a whole is driven by the necessity of reducing the risks of erroneous interpretation of recognition results, increasing the consistency of multi-level management and coordination, as well as ensuring a verifiable transition from diagnostic events to effectively managed actions. Thus, AR/VR and HITL acquire the status not of peripheral technologies, but of an architecturally embedded mechanism for increasing the reliability and adaptability of the management of the elimination of the consequences of emergency events.

At the phase of surveillance and pattern recognition, the cross-cutting HMI layer provides interpretative support for the results of intelligent diagnostics, including visual identification of detected damage to objects, risk zones, as well as the scale of required interventions, and also the recording of changes in the state of the remediation object taking into account confidence/uncertainty assessments. At this phase, HITL mechanisms perform the function of expert validation of critically significant or low-reliability diagnostic events, thereby making it possible to minimize the probability of the transition of false-positive or false-negative results into the managerial loop. At the phase of geospatial integration (GIS/DSS), AR/VR and HITL support the coordination of the spatial context of decisions, namely: visual analysis of access constraints, priority intervention zones, as well as alternative routes for the delivery of various types of resources and the scenario consequences of a specific choice. In this context, VR acquires particular importance as an environment for scenario modeling and collective examination of alternative decisions in the what-if analysis mode, as well as a tool for interagency cooperation and coordination of efforts at the phase of project analysis and before the beginning of field implementation of remediation/reconstruction/recovery works. At the phase of the Decision & Orchestration Core (DSS + BPMN/CPM), HITL mechanisms ensure the controlled inclusion of an expert in the process of making specific decisions where confirmation of the level of safety, prioritization, change of the sequence of remediation tasks, redistribution of resources, or approval of a modification scheme of the process is required. It should be especially emphasized that, at this phase, AR/VR do not replace the orchestration core, but ensure its cognitive transparency, while increasing the quality of interpretation of the consequences of managerial scenarios.

At the phase of Execution Monitoring & Verification, AR acquires the greatest practical significance as a tool of field support in situations of: overlaying risk layers on terrain, routing the delivery of resources and equipment, indicating the statuses of task execution, territorial analysis of the boundaries of intervention zones, as well as analysis of infrastructural constraints. This makes it possible to reduce the level of errors in execution, increase the compliance of actual actions with the previously formed plan, and accelerate the confirmation of completed operations. HITL at this phase makes it possible to verify the obtained results, record deviations, and, if necessary, make a decision on re-inspection and/or corrective actions. At the phase of Feedback Learning & Adaptive Refinement, VR and HITL may be used for post-scenario analysis, as well as for the purpose of modifying the course of remediation operations, identifying the causes of delays, routing conflicts, and interpretation errors, as well as for adapting procedures, confidence thresholds, and BPMN regulations. Thus, AR/VR and HITL become not only means of supporting the entire cycle of implementation of remediation measures, but also tools of management, organizational learning, and a base of practical knowledge within the management loop. Taken together, all of the above forms continuous human-machine support at all stages of the lifecycle of remediation logistics.

Summarizing the description of this approach, it may be stated that the scientific novelty lies in the conceptualization of AR/VR and Human-in-the-Loop mechanisms as a cross-cutting HMI layer in the architecture of the closed digital diagnostic-managerial loop, rather than as local tools of visualization or training. The proposed expansion of the role makes it possible to formally connect digital diagnostics, process orchestration, and the field implementation of the complex of remediation measures through a unified loop of interpretation, coordination, and verification of decisions. In contrast to fragmented approaches, where AR/VR and expert participation are integrated in most cases episodically, in this concept they act as a systemic mechanism for increasing the resilience of management under conditions of uncertainty, time scarcity, and high dynamics of situational changes. This strengthens the architectural integrity of the model proposed by the authors of the monograph and substantiates its applicability to the tasks of eliminating the consequences of emergency situations of a natural, technogenic, and military nature, as well as to post-crisis remediation measures (**Table 4.2**).

This matrix appears methodologically strong and useful, as it performs not merely an illustrative, but a substantiating function within the structure of the study. First, it demonstrates the functional continuity of human-machine interaction throughout the entire loop, namely: from the interpretation of observation results and image recognition to the verification of damage, from training to the modification of the remediation logistics route. This means that human participation and immersive interfaces are embedded not in a single separate stage, but in the logic of the entire management lifecycle. Second, the matrix confirms the differentiation of the roles of AR, VR, and HITL. That is, the matrix demonstrates that the technologies are distributed not arbitrarily, but in accordance with their most rational function within the management architecture. Third, the table confirms that the concept proposed by the authors indeed ensures cognitive, coordination, and operational connectedness between digital diagnostics, decision-making, process orchestration, as well as the field implementation of the set of remediation/reconstruction/recovery measures, verification of results, and subsequent adaptive training of personnel. This is particularly important, because it is precisely such connectedness that is usually lacking in many existing digital solutions, where analytics, management, and execution remain disconnected. Fourth, the matrix formed by the authors confirms the thesis that the HMI layer is not an auxiliary, but an architecturally significant mechanism for increasing the resilience of crisis management under conditions of uncertainty, time scarcity, high dynamics of situational change, increasing the effectiveness of interagency cooperation and coordination of joint efforts for the purpose of the prompt elimination of the consequences of emergency events, as well as the necessity of a rapid transition from diagnostics to real actions. Fifth, this matrix also indirectly confirms the closed nature of the loop itself, since the functions of AR/VR and HITL are distributed not only at the input and in the middle of the process, but also at the final stages, namely at the stages of verification, learning, and adaptive refinement. And this means that the loop is indeed considered as a cycle, rather than as a linear chain of actions.

Table 4.2 Matrix of functional distribution of AR/VR and Human-in-the-Loop mechanisms by phases of the closed digital diagnostic-managerial loop of remediation logistics

Loop phases/ HMI functions	Interpretation	Validation	Coordination	Scenario analysis	Field support	Verification	Learning/ adaptation
Surveillance Data Acquisition	± (coverage control)	–	–	–	–	–	–
Pattern Recognition & Diagnostic Analytics	AR/VR + HITL	HITL	–	–	–	–	–
Geospatial Diagnostic Integration (GIS)	AR/VR	HITL	AR/VR + HITL	VR	–	–	–
Decision & Orchestration Core (DSS + + BPMN/ CPM)	–	HITL	AR/VR + HITL	VR + HITL	–	–	–
Execution Monitoring & Verification	AR	HITL	–	–	AR + HITL	AR + HITL	–
Feedback Learning & Adaptive Refinement	VR + HITL	HITL	HITL	VR	–	HITL	VR + HITL

In general form, presented below is an aggregated list of what is included in AR/VR as parts of the cross-cutting HMI layer:

1. Augmented Reality for field operations support, in particular for: overlaying digital layers on terrain/a tablet screen (including, among other things,

the designation of risk zones, routes, statuses of tasks being performed, as well as access restrictions).

2. Augmented Reality for geospatial data visualization, including for the display of GIS layers and diagnostic objects referenced to real space.

3. Augmented Reality for plan-vs-actual verification, in the context of comparing planned remediation tasks with the work actually performed on site.

4. Augmented Reality for field navigation and routing support, including visual prompts regarding safe routes, access points, as well as bypassing hazardous zones.

5. Virtual Reality for scenario simulation, including the playing out of alternative scenarios of work execution, logistical routes, and sequences of actions.

6. Virtual Reality for team training and preparedness, which may be successfully used for practicing response mechanisms, coordination, and task execution under conditions as close as possible to real ones.

7. Virtual Reality for what-if analysis of management decisions, which may be used for visual verification of the consequences of changing priorities, timeframes for the implementation of remediation measures, routes for resource delivery, and their distribution.

8. Virtual Reality for cross-level decision coordination, which may be applicable in training of joint scenarios for the strategic, regional, and field levels of management of different types of remediation/reconstruction/recovery measures.

9. Immersive visualization of diagnostic outputs, which consists in the presentation of the results of recognition/segmentation/detection in a form maximally understandable for operational human interpretation.

10. Immersive visualization of model uncertainty and confidence, including the display of confidence/uncertainty estimates for reducing the risk of erroneous interpretation of AI analytics.

11. AR/VR as a human-machine interface layer in the loop. Let's emphasize that this is not merely visualization, but a means of interpretation, coordination, as well as confirmation and verification of decisions.

12. AR/VR as a means of after-action review and learning. This refers to the application of VR/AR in the feedback phase for the analysis of errors, refinement of processes, and team training [22, 23].

Thus, it is possible to make a generalization: AR in the proposed architecture is predominantly oriented toward supporting field execution and verification, whereas VR is oriented toward scenario planning, decision coordination, and learning (AR supports execution and verification; VR supports simulation, coordination, and learning).

As a result, there is every basis to present a kind of "Evolutionary Ladder" of the development and expansion of the role of AR/VR:

Visualization tool → Situational awareness support → Decision support interface → Execution support interface → Verification interface → Cross-cutting HMI layer in closed-loop management (**Fig. 4.4**).

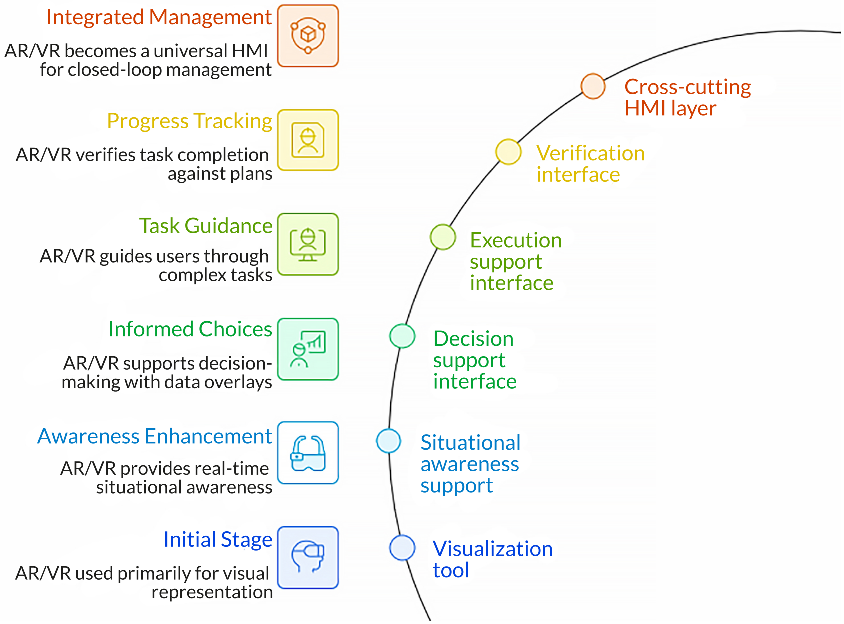

Fig. 4.4 Evolutionary ladder of the AR/VR role in remediation logistics management

4.7 Conclusions

The authors have proposed a conceptual architecture of a closed digital diagnostic-managerial loop for remediation logistics, in which the Pattern Recognition block is formalized as a source of diagnostic events and uncertainty, integrated into the geospatial layer and further transformed into executable managerial actions through the Decision & Orchestration Core (DSS + BPMN/CPM), with cross-cutting support of the HMI layer (AR/VR + Human-in-the-Loop). One of the key properties of the proposed architecture is its adaptive architectural reconfigurability, understood as the ability of the closed digital diagnostic-managerial loop to change the configuration of functional blocks, the connections between them, and the parameters of process orchestration depending on the type of emergency situation, the stage of remediation, and resource constraints. The proposed approach demonstrates both quantitative and qualitative advantages compared to fragmented solutions. From a quantitative perspective, it enables the evaluation of the degree of closure of the full management cycle from diagnostic events to evidence-based and traceable state updates. From a qualitative perspective, it ensures the integration of previously fragmented components into a unified adaptive architecture capable of transforming diagnostic results into executable and verifiable managerial actions.

The monograph presents an analysis of the expansion of the horizon of applicability of the proposed conceptual approach to the tasks of eliminating the consequences of emergency situations of a natural, technogenic, and military nature, while preserving the transport-logistics sphere as the priority domain of implementation. The study focused attention on the transport-logistics sphere as the priority contour for approbation and development, since it is precisely in it that the necessity of rapid transformation of diagnostic data into executable managerial actions is most clearly manifested [24].

In addition, the scientific novelty of the study lies in the conceptual rethinking of the AR/VR role in systems for eliminating the consequences of emergency situations and remediation of affected territories: AR/VR are proposed to be considered not as isolated tools of visualization or training, but as a cross-cutting layer of human-machine interaction (cross-cutting HMI layer) in the architecture of the closed digital diagnostic-managerial loop. In contrast to traditional approaches, AR/VR are embedded into a unified loop together with pattern recognition, GIS, DSS, and BPMN/CPM, ensuring the transition from the results of digital diagnostics to executable managerial actions in the tasks of eliminating destruction, reconstruction, construction, repair, and full remediation of territories. It is substantiated that under modern conditions of high uncertainty, scarcity of time and resources, AR/VR acquire new functional characteristics, namely: support for the interpretation of diagnostics, coordination of decisions, support of execution, verification of results, as well as training and adaptive adjustment of the loop. Thus, the range of their application is significantly expanded – from local visual support to an architecturally significant component of the engineering of managerial processes in a multi-actor crisis environment. The proposed approach forms a basis for further formalization and empirical approbation of integrated diagnostic-managerial systems of a new generation in subsequent studies.

Conflict of interest

The authors declare the absence of any conflicts of interest in relation to this monograph chapter and its published results, including financial interests, non-financial personal relationships, as well as other institutional interests that could have influenced the work performed.

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Data availability

This chapter has a conceptual-methodological character and does not rely on empirical data. The materials supporting the results of this study (including conceptual diagrams, metric definitions, and formalized hypotheses, etc.) were developed by the authors and may be provided upon reasonable request.

Use of artificial intelligence statement

The authors used artificial intelligence technologies exclusively for language and academic-style support, specifically for verifying the correctness, consistency, and clarity of the English wording, as well as for minor stylistic refinement. In particular, the authors used the generative language model ChatGPT (OpenAI, GPT-5.2 Thinking) for language checking and limited editorial editing. The authors bear full responsibility for the content of the final version of the manuscript; the AI tool is not credited as an author and is not responsible for the reported results.

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Authors' contributions

Tetiana Cherniavska: Conceptualization; Theoretical framework.

Bohdan Cherniavskyi: Methodology; Architectural structuring support.

Rusnak Alla: Interpretation of results; Development of the closed-loop architecture.

Nadtochii Iryna: Writing – original draft; Writing – review & editing.

Artur Harahulia: Visualization (figures and scheme logic).

Oleksii Bobrovskyi: Formal analysis; Analysis of scientific sources.

All authors contributed to the scientific content of this chapter, jointly developed the conceptual idea and structure of the work, and approved the final version of the manuscript.

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