ECOLOGICAL SYSTEMS MODELING

Edited by
Tetiana Cherniavska

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Collective monograph

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Tetiana Cherniavska (Editor)

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AUTHORS

Chapter 1

Andrii Onyshchenko
Doctor of Economic Sciences, Professor
Department of Information Systems and Technologies
Taras Shevchenko National University of Kyiv
ORCID: https://orcid.org/0000-0002-3194-1116

Volodymyr Kudin
Doctor of Technical Sciences, Professor
Department of Intellectual and Information Systems
Taras Shevchenko National University of Kyiv
ORCID: https://orcid.org/0009-0005-9071-1213

Olena Lytvyn
PhD, Associate Professor
Department of International Finance
Taras Shevchenko National University of Kyiv
ORCID: https://orcid.org/0000-0003-3437-2067

Halyna Kashcheieva
PhD, Associate Professor, Director
Representation of the Private Joint-Stock Company "Higher Educational Institution "Interregional Academy of Personnel Management "Berezansky Institute"
ORCID: https://orcid.org/0000-0002-6684-3057

Chapter 2

Valerii Samsonkin
Doctor of Technical Sciences, Professor
Department of Transport Technology and Process Control Traffic
National Transport University
ORCID: https://orcid.org/0000-0002-1521-2263

Iuliia Bulgakova
PhD, Associate Professor
Department of Management of Commercial Activity of Railways
National Transport University
ORCID: https://orcid.org/0000-0003-3948-9731

Oksana Yurchenko
PhD, Associate Professor
Department of Management of Commercial Activity of Railways
National Transport University
ORCID: https://orcid.org/0000-0001-6834-692X

Chapter 3

Roza Mammadova
PhD, Associate Professor
Department of Molecular Biology and Biotechnologies
Baku State University
ORCID: https://orcid.org/0000-0001-8978-374X

Turkan Hasanova
PhD, Associate Professor
Department of Soil Science and Real Estate Cadastre
Baku State University
ORCID: https://orcid.org/0000-0002-5040-2599

Matanat Aliyeva
PhD, Associate Professor
Department of Soil Biology
Ministry of Science and Education Republic of Azerbaijan, Institute of Soil Science and Agrochemistry
ORCID: https://orcid.org/0000-0002-0298-8345

Chapter 4

Bohdan Cherniavskyi
PhD, Adjunct
Department of Economics and Technical Sciences
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0001-9174-6139

Chapter 5

Viktoriia Petrenko
Doctor of Science in Economics,
Associate Professor, Head of Department
Department of Finance, Accounting and Entrepreneurship
Kherson State University
ORCID: https://orcid.org/0000-0001-8336-7665

Alla Karnaushenko
PhD, Associate Professor
Department of Entrepreneurship, Accounting and Finance
Kherson State Agrarian and Economic University
ORCID: https://orcid.org/0000-0003-1813-2792

Kateryna Melnykova
PhD, Dean
Department of Finance, Accounting and Entrepreneurship
Kherson State University
ORCID: https://orcid.org/0000-0001-6415-5667

Chapter 6

Masuma Mammadova
Doctor of Sciences of Engineering, Professor, Head of Department
Department No. 11
Institute of Information Technology of Ministry of Science and Education of the Republic of Azerbaijan
ORCID: https://orcid.org/0000-0002-2205-1023

Tetyana Baydyk
Doctor of Sciences of Engineering, Professor
Department of Micro and Nanotechnology
Institute of Applied Sciences and Technology (ICAT)
National Autonomous University of Mexico (UNAM)
ORCID: https://orcid.org/0000-0002-3095-2032

Zarifa Jabrayilova
Doctor of Sciences of Engineering, Associate Professor, Chief Researcher
Department No. 11
Institute of Information Technology of Ministry of Science and Education of the Republic of Azerbaijan
ORCID: https://orcid.org/0000-0002-9661-5805

Huseyn Gasimov
PhD of Engineering, Head of Department
Department of Electronics and Information Technologies
Nakhchivan State University
ORCID: https://orcid.org/0000-0002-3714-875X

Turkan Alibeyli
PhD Student
Department of Electronics and Information Technologies
Nakhchivan State University
ORCID: https://orcid.org/0009-0000-6709-6770

Chapter 7

Alla Karnaushenko
PhD, Associate Professor
Department of Entrepreneurship, Accounting and Finance
Kherson State Agrarian and Economic University
ORCID: https://orcid.org/0000-0003-1813-2792

Lesia Kononenko
PhD, Associate Professor
Department of Entrepreneurship, Accounting and Finance
Kherson State Agrarian and Economic University
ORCID: https://orcid.org/0000-0001-5698-5003

Viktoriia Petrenko
Doctor of Economic Sciences, Associate Professor, Head of Department
Department of Finance, Accounting and Entrepreneurship
Kherson State University
ORCID: https://orcid.org/0000-0001-8336-7665

Yuliia Hlavatska
PhD, Associate Professor
Department of Public Administration, Law and Humanities
Kherson State Agrarian and Economic University
ORCID: https://orcid.org/0000-0002-1162-0251

Nataliia Sysolina
PhD, Associate Professor
Department of Economics, Entrepreneurship and Hotel and Restaurant Business
Central Ukrainian National Technical University
ORCID: https://orcid.org/0000-0003-0101-8854

Iryna Sysolina
PhD, Associate Professor
Department of Agricultural Mechanical Engineering
Central Ukrainian National Technical University
ORCID: https://orcid.org/0000-0002-2168-6553

Chapter 8

Tetiana Cherniavska
Doctor of Economic Sciences, Professor
Department of Economics and Technical Sciences
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0002-4729-2157

Viktor Nadtochii
PhD, Associate Professor
Department of Automatics and Electrical Equipment
Kherson Educational-Scientific Institute of Admiral Makarov National University of Shipbuilding
ORCID: https://orcid.org/0000-0003-3869-3546

Anatolii Nadtochyi
PhD, Associate Professor, Acting Head of Department
Department of Automatics and Electrical Equipment
Kherson Educational-Scientific Institute of Admiral Makarov National University of Shipbuilding
ORCID: https://orcid.org/0000-0003-1905-0895

Dmytro Lomonosov
PhD, Associate Professor
Department of Economics
Kherson Educational-Scientific Institute of Admiral Makarov National University of Shipbuilding
ORCID: https://orcid.org/0000-0003-4394-1807

Robert Cieślak
PhD, Head of Department
Department of Technical Science
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0002-1320-0410

Bohdan Cherniavskyi
PhD, Adjunct
Department of Economics and Technical Sciences
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0001-9174-6139

Chapter 9

Tetiana Cherniavska
Doctor of Economic Sciences, Professor
Department of Economics and Technical Sciences
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0002-4729-2157

Artur Zimny
Doctor of Science in Economics, Professor, Rector
State University of Applied Sciences in Konin
ORCID: https://orcid.org/0000-0002-8025-550X

Alla Rusnak
Doctor of Economic Sciences, Professor,
Acting Head of Department
Department of Economics
Kherson Educational-Scientific Institute of Admiral Makarov National University of Shipbuilding
ORCID: https://orcid.org/0000-0002-3198-2866

Iryna Nadtochii
Doctor of Economic Sciences, Professor, Associate Director Education and Research
Kherson Educational-Scientific Institute of Admiral Makarov National University of Shipbuilding
ORCID: https://orcid.org/0000-0003-0693-8000

Inna Naida
PhD, Associate Professor
Department of Law
Kyiv Cooperative Institute of Business and Law
ORCID: https://orcid.org/0000-0001-7296-7884

Mykola Skarzhynskyi
PhD, Associate Professor
Department of Law
Kyiv Cooperative Institute of Business and Law
ORCID: https://orcid.org/0009-0005-0762-8591

ABSTRACT

The collective monograph "Ecological systems modeling" presents an interdisciplinary inquiry that integrates the methodology of ecological and socio-economic modeling with digital instruments for governing sustainable development and territorial recovery. The central concern is the balance between the economy and the natural environment through the lens of the Sustainable Development Goals (SDGs) and the Paris Agreement.

The concept of transition to a balanced sustainable development model

This chapter elaborates a methodology for reconciling economic and environmental constraints within the logic of the SDGs and the Paris Agreement, grounded in inter-industry eco-economic input-output models and the Method of Basis Matrices (MBM). The authors set out an approach to solving both forward and inverse problems to identify a preferred development pathway and to iteratively retune the model under alternative sustainability scenarios. The resulting trajectories are recommended for long-term planning and for improving policy at national and international levels.

Cost assessment of climate change impacts on a railway company

This chapter proposes a practice-oriented framework for accounting for and attributing climate-related costs (incidents, maintenance, passenger behavior) in the railway sector. Emphasis is placed on separating climate-attributable expenditures from ordinary costs, avoiding double counting, and building a structured repository of baseline and climate-linked data. The chapter underscores the need for further research on passenger behavioral responses to extreme weather.

Ecological state of modern soil cover in agrocenoses of the Greater Caucasus Sheki region

This chapter offers an in-depth analysis of climatic and soil-microbiological data (2023–2024) for agrocenoses in the Sheki district, including moisture, humus content, actinomycete abundance, and dominant micromycete taxa. The effects of reforestation are documented, as is the role of long-lived stand fractions in accumulating organic matter (21.5–32.7 $kg \cdot m^{-2}$). The study demonstrates the significance of microbiological indicators – such as colony-forming units (CFU) and microbial biomass C – for monitoring and rational use of gray forest soils.

Information technologies in scenario-based modeling of post-conflict territory remediation: from express sanitation to sustainable recovery

The author proposes a hybrid architectural model (ML + GIS + IoT) and optimization algorithms for scenario-driven remediation management across the

I-S-R phases (Invasion-Stabilization-Recovery) in Ukrainian territories affected by military activity. Case studies from Kherson, Zaporizhzhia, and Kharkiv substantiate prioritized measures (hydro-ecological monitoring, radiation control, pollution mapping, and soil/water remediation). Validation matrices and heat maps are employed to select digital components, thereby accelerating the transition from rapid clean-up to sustainable recovery.

Sustainable development policy for post-conflict recovery in Ukraine: the role of environmental indicators in decision-making

By the collective of authors of the monographic study, on the basis of a survey of $>$ 16,000 residents of 42 de-occupied communities of southern Ukraine, five indicators (TPMA, DNES, IHWI, ANR, BPHP) are presented. The authors propose to use heat maps and a structural model of managerial decisions for the purposes of ranking "hot spots" and forming local strategies (monitoring, reclamation, waste management, education). A structural model of management of decisions has been formed and sources of financing are indicated (donors, national funds, PPP); directions of future research have been outlined, including a national index of environmental sustainability of post-conflict territories.

Development of models and methods for assessing green skills in the labor market ecologization environment

This chapter presents an intelligent approach to aligning supply and demand for "green" occupations using fuzzy multi-criteria methods and pattern recognition. Scenarios are provided for matching competencies to vacancy-specific requirements, and the method's invariance is demonstrated across diverse segments of the green economy.

Shared use of transport as a component of the circular economy in relation to achieving sustainable development goals

The chapter examines the applicability of shared-mobility models (car-sharing) in rural communities as a tool of the circular economy and the SDGs. Using the Adzhamka territorial community as a case, it substantiates the viability of local car-sharing (−13.68 t CO_2 per year and savings of 27,000–43,000 UAH per user annually), conditional on sufficient digital readiness and a cooperative model. Scaling barriers (digital divide, limited engagement) are identified, directions for integrating "smart mobility" are outlined, and vectors for future research are proposed.

Organizational and structural modeling of the integration of marine robotics into multilevel environmental and ecological monitoring systems

Here the authors advance an organizational model for integrating marine robotics into multilevel eco- and hydromonitoring, grounded in systems thinking, cybernetics, and ecosystemology. Ten principles (goal-orientation, adaptability, crisis resilience, interoperability, etc.) are formalized mathematically; the model operates through three contours – physical, informational, and managerial. Simulation experiments highlight the decisive role of adaptability and resource efficiency in ensuring system sustainability.

Social entrepreneurship as a driver of green remediation and revitalization of affected territories: digital modeling and decision support systems

The team develops an integrated DSS architecture in which social entrepreneurship acts as a change agent; the TBL → ESG linkage ensures measurability of effects, while LegalTech codifies compliance and auditing of smart contracts. For the Kharkiv region, six scenarios are modeled using cluster dendrograms, PCP, and a "butterfly chart", demonstrating feasible trajectories for employment, soil/water clean-up, and risk reduction under transparent pay-for-performance arrangements. A seamless pipeline – data → analytics → decision → contract → KPI-based payments → verified impact – is proposed for scalable project finance. A pilot for Kharkiv (H2-2026 → 2030) shows gains in employment and training, progress in soil/water remediation, and improved governability; the visualization tools support priority-setting by cluster.

Keywords

Sustainable Development Goals (SDGs), Paris Agreement, Ecological-economic input-output models, Method of Basis Matrices (MBM), Climate-related costs in the railway sector, Passenger behavioral changes, Gray forest soils, Actinomycetes, Microbial biomass (CFU, Cmic), Post-conflict territory remediation, Revitalization, Scenario-based modeling (I-S-R), Geographic Information Systems (GIS), Machine Learning (ML), Internet of Things (IoT), Multi-criteria Decision Analysis (MCDA), Validity matrices and heat maps, Environmental indicators TPMA, DNES, IHWI, ANR, BPHP, Structural decision-making model, Green skills and occupations, Shared mobility (car sharing), Circular economy, Marine robotics, Decision Support System (DSS), ESG and smart contracts, LegalTech, Resource efficiency and adaptability.

CIRCLE OF READERS AND SCOPE OF APPLICATION

The collective monograph "Ecological systems modeling" is addressed to a broad community of researchers and practitioners in ecological modeling, economic geography and environmental management, public administration, transport and infrastructure management, agronomy and soil science, environmental security, automation and robotic systems, data science (GIS/ML/IoT), as well as social entrepreneurship and impact finance. It will be of value to policymakers, municipal and regional authorities, NGOs, international donors, and private stakeholders engaged in addressing pressing, real-world challenges.

The scope of application of the research findings presented in the monograph includes:

– *Macro-modeling and policy design within the SDG framework.* Application of intersectoral ecological-economic models and the Method of Basic Matrices (MBM) to derive feasible development trajectories ("mainlines"), test scenarios, and substantiate long-term planning and legislation in alignment with the Paris Agreement;

– *Cost assessment of climate adaptation in the railway sector.* A practical taxonomy and methodology for separating climate-attributable costs from routine operating expenditures, building structured baseline datasets, and supporting investment decisions aimed at enhancing the resilience of railway operators;

– *Monitoring of agroecosystems and soil health.* Field protocols and microbiological/biochemical indicators (e.g., CFU, microbial biomass carbon, dominant micromycete species) to inform land-use decisions, forest restoration, and the prudent management of grey forest soils;

– *Digital, scenario-based remediation management.* A hybrid ML + GIS + IoT architecture using validity matrices and heat maps to select digital components and to govern the transition from express sanitation to sustainable recovery across the I-S-R phases;

– *Environmental indicators for decision-making in post-conflict territories.* A settlement/community-level framework (TPMA, DNES, IHWI, ANR, BPHP) with heat-map visualization to identify "hot spots", prioritize interventions, and structure local recovery strategies;

– *Human capital for the green economy.* Fuzzy multi-criteria models for assessing green skills, matching supply and demand for green jobs, and supporting recruitment/HR planning amid the greening of the labor market;

– *Shared mobility in the circular-economy paradigm.* An evidence base and deployment methodologies for cooperative car-sharing in rural communities (estimating

CO_2 reductions and user savings), together with guidance on digital readiness, governance, and scaling barriers;

– *Marine robotics in multi-level eco-monitoring.* An organizational and structural model (physical, information, and managerial circuits) and formalized principles for integrating marine robotic operations (MRO) into national monitoring systems and water-resource remediation;

– *Project governance for social entrepreneurship oriented toward verified impact in lean recovery through green remediation and the revitalization of war-damaged territories.* An integrated DSS linking TBL $\rightarrow$ ESG, LegalTech (smart-contract compliance/audit), and analytics (GIS/MCDA/portfolio optimization) to finance and scale green remediation via transparent pay-for-results mechanisms.

Accordingly, the monograph functions both as a methodological compendium and a practical guide for the design, piloting, and scaling of sustainable development – grounded in quantitative models, modern digital infrastructures, and verifiable impact.

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INTRODUCTION

Current issues in ecological systems modeling: from stability theory to the digital practice of recovery

Tetiana Cherniavska

It is now widely recognized that ecological modeling is rapidly evolving from an academic field into an applied instrument of global security and sustainable development. Accelerating climate change, the depletion of natural capital, and the rising frequency of extreme events of diverse nature and scale make the development of precise and reproducible models a shared priority for all states. The theory of ecosystem stability and resilience provides the conceptual framework for assessing permissible ranges of variation and the risks of shifts to undesirable states. In the twenty-first century, this framework is complemented by a digital practice of recovery, in which decisions are informed by data from satellites, sensor networks, unmanned systems, and geoinformation platforms.

The monograph advances an interdisciplinary integration of ecological-economic models, optimization methods, and contemporary ICTs, deliberately marrying academic rigor with managerial applicability. For countries at different income levels, comparability of indicators and transparency of methods are essential; these are ensured through standardized metrics and verification procedures. In the domain of climate adaptation for transport systems, cost and vulnerability models enable accurate attribution of climate-related expenditures and guide investment planning toward sustainable development objectives. At the agroecosystem level, the integration of field protocols, microbiological markers, and remote sensing makes evidence-based land-use and soil restoration decisions possible.

For aquatic ecosystems and broader environmental security, digital twins and robotic platforms are gaining prominence by ensuring continuity of observations and rapid response. Post-conflict and post-disaster territories require scenario-based remediation management, wherein models guide the transition from emergency sanitation to long-term recovery and revitalization. In such contexts, multi-criteria assessment, probabilistic modeling, and sensitivity analysis substantially enhance

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decision quality under high uncertainty. Environmental indicators aggregated at community and regional scales enable the construction of hot-spot maps to prioritize the allocation of scarce resources. A critical direction, moreover, is coupling models with policy, translating quantitative analyses into regulatory norms, adaptation strategies, and investment plans.

Contemporary approaches call for end-to-end digital pipelines – "data → analytics → decision → contract → pay-for-results" – that ensure controllability and accountability. The synergy of ESG frameworks, legal technologies, and decision-support systems makes it possible to measure the effects of environmental projects while reducing investor risk. The circular-economy paradigm and shared mobility illustrate how models of demand, emissions, and resource savings can steer local initiatives with scalable impact. In parallel, models for the development of "green" skills are being designed to align education policy, business needs, and regional employment trajectories. A key challenge lies in bridging spatial and temporal scales, where local processes directly shape national and global outcomes.

In budget-constrained settings, methods that rapidly identify high-return leverage points and optimize portfolios of conservation projects are especially valuable. In this context, digital models for integrated governance of green remediation and the revitalization of post-war territories – drawing on social-entrepreneurship instruments, modern DSS, and LegalTech platforms are of particular importance. The growing availability of open data and computational power makes replication of the models proposed in this monograph, and their adaptation to local conditions, practically feasible for most countries. Taken together, these developments provide the foundation for evidence-informed policy and help to balance ecological limits with socio-economic objectives.

Accordingly, the studies presented in this monograph on ecological systems modeling transcend disciplinary boundaries, becoming the core of strategic risk governance and sustainable development. Collectively, they set the agenda for a scholarly and practical dialogue in which sustainability is treated as a computable property, and recovery – as a reproducible digital practice.

CHAPTER 1

The concept of transition to a balanced sustainable development model

Andrii Onyshchenko
Volodymyr Kudin
Olena Lytvyn
Halyna Kashcheieva

Abstract

Sustainable Development Goals pose new challenges for economies, which need to adapt their operations and strategies to the requirements of the SDGs. The object of the study is the system of ecological, economic, social and political relations in the process of sustainable development of a market economy in the context of implementation of the provisions of the Paris Agreement. The issue to be solved is analyzing the concept of sustainable development, the methodology for studying the interaction between the economy and the environment, to clarify their content using a balanced approach to economic, social and environmental tasks in modern conditions, and, as a result, to identify the main trajectories among the possible ones. The mathematical tools for modeling and analyzing the sustainable development of the economic system with regard to the Paris Agreement have been developed; the proposed methodology and tools allow analyzing the impact of environmental constraints on economic development at the level of intersectoral interaction. The interpretation of the results obtained is that it is possible to determine the macroeconomic parameters of the national sustainable development with ensuring both economic and environmental balance. The practical experience of using inter-sectoral models to solve environmental problems and rational use of resources shows the need for their application in the system of macroeconomic sectoral and regional models, and the obtained main trajectories – in the system of long-term planning. The peculiarity of the obtained results lies in the application of the method of basic matrices to the study of balance ecological and economic models of "input-output" based on the method of basic matrices and the possibility of its application in conditions of poor conditionality of the matrix structure. The proposed provisions,

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recommendations and conclusions can be used in the sustainable development of relevant legislation and laws at the national and international levels.

Keywords

Sustainable development goals, Paris Agreement, matrix ecological and economic models, productivity, parametric system synthesis.

1.1 Introduction

The modern type of economic development is defined as a technogenic type of socio-economic development. This type can be characterized as a nature-intensive type of sustainable development based on the use of artificial means of production that are created and function without regard to environmental constraints and stimulate the unlimited growth in the consumption of goods. As a result of human activity, the environment has begun to have an unprecedentedly destructive impact. If the current trends continue, the use of natural resources, pollution, and greenhouse gas emissions will increase several times over the next half century. Meanwhile, sustainable economic development must take into account at least three increasingly obvious environmental constraints:

– limited capacity of the environment to absorb, assimilate various kinds of waste, pollution, greenhouse gases caused by economic systems;

– degradation of renewable natural resources as a result of overexploitation;

– a finite amount of non-renewable resources.

Ignoring these limitations and the unlimited development of the technogenic type of the world economy has led to global environmental problems. As defined in the third assessment report of the Intergovernmental Panel on Climate Change, "climate change is a problem with unique characteristics. It is global, long-term and encompasses a complex of interactions between climatic, environmental, economic, political, institutional, social and technological processes" [1]. Thus, unlike other global problems, global climate change is more complex, multisystem, multilevel and multicomponent.

The adoption by the United Nations of the Paris Agreement (PA) on climate protection, which, in particular, aims to reduce greenhouse gas emissions globally, was a relevant step in preventing further deepening of these threats and the problems of the negative impact of climate change on sustainable socio-economic development [2].

In early July 2021, the European Commission presented a package of legislative initiatives "Fit for 55" to implement the European Green Deal and ensure a 55% reduction in greenhouse gas emissions in the EU by 2030 from 1990 levels. In October 2023, the work on preparing the necessary legislative framework was finally completed [3]. Relevant initiatives were also adopted by the Government of Ukraine in the form of the Updated National Determined Contribution to the Paris Agreement (NDC2), which declares a national target for reducing greenhouse gas emissions. By 2030, this reduction should be 65% compared to 1990 [4].

An illustrative instance may be seen in the study conducted by W. Zhang, M. Zhang, Sh. Wu, F. Liu, whereby the authors employed the four indicators of low-carbon economic benefits, low-carbon technology stock, low-carbon human resources, and CO_2 emissions reflect the level of low-carbon sustainable development of enterprises. The results show that the level of low-carbon sustainable development of enterprises is not high (<0.6); low-carbon human resources have two stages of decline and rise; government supervision and low-carbon technology can significantly reduce CO_2 emissions. However, multi-scenario simulation results show that in the early stage of low-carbon sustainable development of enterprise, excessive government supervision will reduce the low-carbon economic benefits of enterprise. The scholars indicate that within 10 years, policy supervision can reduce CO_2 emissions by up to 67% and increase low-carbon benefits by 17%; low-carbon technology can reduce CO_2 emissions by up to 60% and increase low-carbon benefits 33% [5].

It is increasingly clear that the traditional model of the economic growth, which ignores the importance of natural factors and is unable to prevent the aggravation of global environmental problems, has exhausted itself. Thus, the development of new predictive models of the sustainable development with a feedback loop – a mechanism for analyzing the effects of the implementation of sustainable development guidelines on the participants in the process, including the environment – has become urgent.

In this case, it would be a reasonable step to move to the level of mathematical modeling of ecological and economic interaction as an effective tool for scientific knowledge. Including the construction of the sustainable development highway in the context of the study of the ecological and economic process in the course of modeling provides a feedback in the system. So, the solution of the main problem mathematically determines the relevant structural elements of the system (matrix and vector of constraints), and also indicates how the found (desired) parameters of reorganization correspond to the inherent technological capabilities (tolerances) for changes. The direction and size of the sustainable development step along the main line should also be in line with the permissible changes. The study of the aforementioned inverse problem to realize the directed evolution of the system in the course of modeling is important and relevant.

1.2 Key concept of mathematical modeling in ecology and economy

The issue of mathematical modeling of the interaction between the economy and the environment within the framework of the Kyoto Protocol is not new. The first class of such models can be called inter-sectoral balance models, which investigate the impact of the economic structure on the environment. According to L. Buiak, O. Bashutska, K. Pryshliak, V. Hryhorkiv, M. Hryhorkiv and V. Kobets, this class of models includes the Leontief-Ford inter-sectoral model and its generalization. In our opinion, the main disadvantage of this class of models is their inability to represent the impact of economic instruments for reducing greenhouse gas emissions on the behavior of market participants. At the same time, a fundamental issue from an economic point of view is related to the extent to which the system formed by the coal market allows economic agents to fulfill their obligations at minimal cost [6].

Numerous studies show that such entities will receive significant economic benefits from participating in the agreement, taking into account the cost of the carbon allowance, as well as the associated benefits from greenhouse gas emission reduction projects. At the same time, C. Böhringer, S. Peterson, T. Rutherford, J. Schneider, M. Winkler suppose that the Kyoto Protocol and the Paris Agreement may create barriers to economic growth if greenhouse gas emissions exceed the level of obligations set for the agent. Thus, there is a need to study a complex, integrated economic and environmental problem and find a balanced solution [7].

Furthermore, the models proposed by R. Sun and studied for the construction of main trajectories in the case of dynamic systems do not reflect their analogues for static balance models. This fact causes a gap and lack of full interconnection between static and dynamic input-output balance models. Moreover, he supposes that economic models play a crucial role in policy formulation, enabling proactive analysis to minimize unintended consequences and maximize policy effectiveness, benefiting both individuals and society. These models also aid decision-making by providing quantitative frameworks to evaluate different options, reducing uncertainty and risk [8].

The analysis of balance ecological-economic models by V. Hryhorkiv, L. Buiak, M. Hryhorkiv is based on the study of productivity and does not reflect the impact of controlled changes in technological matrices on the vectors of gross output of the main and auxiliary ecological production. Despite the diversity of such problems, a single functional-analytical approach can be used to study them. Methods for solving systems of linear algebraic equations (SLAE) are fundamental in a number of problems (and not only environmental and economic ones), since it is to their study that the analysis and optimization in the initial formulation is reduced (after simplification and discretization) [9]. High-precision computational schemes in rational and long mantissa numbers are proposed by V. Kudin, V. Onotskyi, A. Al-Ammouri, L. Shkvarchuk. The scholars sustain that comparative schemes of algorithms on the corresponding test libraries were logically supplemented by their application to applied matrix models [10].

At the same time, in contrast to the matrix structures identify that it is logical to consider more general variants of matrix models, for instance, in conditions of poor determinacy of the matrix structure. This will deepen the methodology for modeling and creating a set of mathematical methods and models for the development of the ecological and economic system in the context of implementing a policy to reduce greenhouse gas emissions, the variables of which include the main sustainable economic indicators and the volume of emission quotas as an environmental resource. In our opinion, this should complement the existing methods of management decision-making and increase the efficiency of the economy's transition to sustainable development [10].

Given the current level of production development and the existing production structure, the primary importance in solving the problem of balance is to determine the right priorities in the sustainable development of industries and regions aimed at achieving high end results and accelerating the greening of the sustainable economy. Establishing and maintaining priorities and proportions requires determining the resources required for their implementation, which to some extent complicates the achievement of balance. In such circumstances, it is important to prevent all other sectors from lagging behind and postponing the solution of non-priority but important problems. Prioritized sustainable development of certain industries and intensification of industrial production imply certain structural shifts in the economic system and require appropriate proportions in the growth rates of various structural components of the sustainable economy. The process of optimal system management aimed at flexible response to changes in the volume and structure of needs and the corresponding impact on the volume and structure of production has an important impact on structural changes. Such management actively contributes to improve the structure of the sustainable economy and stabilizing greenhouse gas emissions in current and future planning.

These criteria meet the conditions of the main trajectory, which generally characterizes the optimal program of ecological and economic growth. Furthermore, one of the main results of the analysis of balance-type models is the proof of the existence of a backbone characterized by an unchanged production structure. However, it is not always possible for the system to develop along the main line, i.e. the main line is not always an acceptable trajectory for a given initial state. Nevertheless, the normative value of the backbone is quite important.

The following result follows from the ecological and economic analysis of balance models. The overall planning horizon of the ecological and economic system consists of three segments, namely: movement to a stationary point, movement in the mode of balanced development and transition to the end point. At the same time, the trajectory of balanced exponential growth or the highway as a whole characterizes the optimal program of ecological and economic growth the better, the longer the period of balanced development.

The issue of choosing the optimal development trajectory for a given initial and final state was developed as a basic principle. This principle is based on the following hypothesis: effective trajectories at intermediate stages before the transition to the final state tend to follow the Neumann ray and the longer the horizon of planning the sustainable development of the economic system, the more the effective trajectory coincides with this ray. Samuelson's principle is a strategy for effective long-term economic growth. It means that a system that has left its initial state should reach the ray of maximum balanced growth and then to function for as many planned periods as possible in the mode of such growth, and then to reach the final state.

The validity of the above principle is proved in the mainline theorems. These theorems state that for a sufficiently long period of time, the optimal trajectory of a dynamic model, regardless of the initial and final states or the objective function, is close to the backbone. Models and trajectories for which such theorems are valid are called backbone models. In our opinion, from the backbone theorems, it is possible to formulate the following conclusion: the duration of the start and end segments in the trajectory does not depend on the length of the planning period. Accordingly, as the planning period increases, the part of the trajectory that is located on the main line or in its vicinity increases. The effective trajectory for a long planning period depends mainly on the structural parameters of the model and to a lesser extent on the initial and final states.

Samuelson's principle makes it possible to simplify and solve the problem of choosing an objective function. In particular, the task of choosing end conditions in dynamic problems of prospective sustainable development, to simplify the calculation and analysis of optimal trajectories of the economic system. Since most of these trajectories are close to or coincide with the trajectories of maximum growth. Let's consider that the latter implies the availability of a mathematical apparatus for taking into account the impact of changes (refinements) on the properties of the new model, of course, without the procedure of solving the problem again (initially). It should be noted that models of ecological and economic processes (as linear systems) have a block (cellular) structure – quadrants of the constraint matrix. In particular, the classical scheme of inter-sectoral balance in the first quadrant contains inter-sectoral flows that correspond to functional and structural sectoral relations.

V. Kudin, A. Onyshchenko, I. Onyshchenko affirmed that the relevance of taking this property into account in the modeling process determines the expansion of the scope of application of methods and algorithms to analyze group changes in blocks (quadrants) of the model matrix on the properties of a linear system. In particular, solutions are in the course of improving the model of environmental and economic processes [11].

Thus, it becomes important to introduce a static model adapted to the nature of the development highway and to build appropriate mathematical algorithms. They should be applied to balance ecological and economic models in order to develop ways to transfer the system from one state to another. That is set according to economic and environmental criteria in the study of inverse and trajectory problems. For this purpose, it is necessary to analyze the use of the balance ecological and economic models of the "input-output" type, which provide the allocation of a part of the national product for the implementation of measures to fulfill obligations under the Paris Agreement in order to study the sectoral structure of the economy.

In our opinion, it is necessary to investigate the issue of a targeted transformation of the sectoral structure of the economy using input-output balance ecological and economic models, to build the corresponding main trajectories based on the matrix theory of pseudo-reversal in the context of the implementation of the sectoral program to limit greenhouse gas emissions. The technology of the method of basis matrices is based on solving (and re-solving) direct problems in particular, by the impact of changes on the properties of the model without solving the problem from the beginning. Establishing links between direct and inverse problems based on the method of basis matrices makes it possible to study inverse, mainstream problems (implementation of sustainable development) and also to apply computational procedures (post-solutions) developed for direct problems.

1.3 Sustainability performance

The change in ecosystem services values under plausible scenarios highlight the fundamental role that healthy ecosystems have in achieving global objectives such as the Aichi Targets [12], especially targets 5, 14, 15 of the Convention of Biological Diversity (**Fig. 1.1**), the Sustainable Development Goals [13], in which natural capital (SDGs 6, 7, 13, 14 and 15) is the cornerstone that sustains the rest of the goals, and the 1.5°C temperature increase limit of Paris Agreement of the United Nations Framework Convention on Climate Change [14]. O. Lytvyn debates that the governments should consider incorporating SDG principles into their corporate governance policies and follow relevant guidelines when planning and designing projects [15].

SDGs	Aichi Biodiversity Targets
6. Ensure the availability and sustainable management of water and sanitation for all	8, 11, 14, 15
7. Ensure access to affordable, reliable, sustainable and modern energy for all	5, 7, 14, 15, 19
13. Take urgent actionto combat climate change and its impact	2, 5, 10, 14, 15, 17
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 17, 19
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss	2, 4, 5, 7, 9, 11, 12, 14, 15, 16

Overview of Aichi Biodiversity Targets

Fig. 1.1 Correlation among SDGs and Aichi Biodiversity Targets in 2024
Source: compiled by the authors based on [12, 13]

The cumulative impact of multiple environmental crises is threatening the foundations of planetary ecosystems. In 2023, the world experienced the warmest year on record. For the first time, global temperatures were dangerously close to the 1.5°C lower limit of the Paris Agreement. Global greenhouse gas emissions and atmospheric concentrations of carbon dioxide reached new records yet again in 2022, with no signs of slowing in 2023. Developing and vulnerable countries face vast development challenges. Per capita growth in gross domestic product (GDP) in half the world's most vulnerable countries is now slower than in advanced economies for the first time this century [16]. This trajectory threatens to reverse a long-term trend towards more income equality among countries. Furthermore, after a decade of rapid debt accumulation, the external debt stock in low- and middle-income countries remains at unprecedentedly high levels.

The progress assessment carried out in 2024 reveals that the world is severely off track to realize the 2030 Agenda. Of the 169 targets, 135 can be assessed using available global trend data from the 2015 baseline to the most recent year, along with custodian agency analyses; 34 targets lack sufficient trend data or additional analysis [16]. Among the assessable targets, only 17 percent display progress sufficient for achievement by 2030 (**Fig. 1.2**).

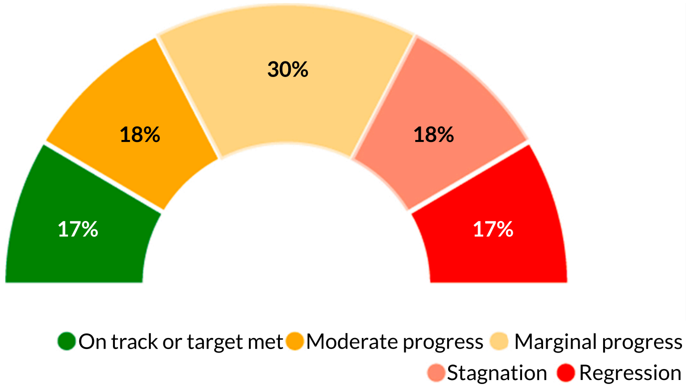

Fig. 1.2 Overall progress across targets based on 2015–2024 global aggregated data
Source: [16]

Nearly half (48%) exhibit moderate to severe deviations from the desired trajectory, with 30% showing marginal progress and 18% moderate progress. Alarmingly, 18% indicate stagnation and 17% regression below the 2015 baseline levels (**Fig. 1.3**). This comprehensive assessment underscores the urgent need for intensified efforts to put the SDGs on course.

As part of sustainable development, O. Lytvyn, A. Onyshchenko and O. Ostapenko sustain that post-war companies in Ukraine should increase their activities in the field of renewable energy and ecology, as well as support environmental projects in any way possible, thus contributing to the achievement of the 6th, 7th and 13th Global Goals for Sustainable Development, which the United Nations has set for 2015. Ukrainian companies should be aware of their environmental impact and strive to reduce it by developing their sustainability orientation, including sustainable business and sustainable management [17].

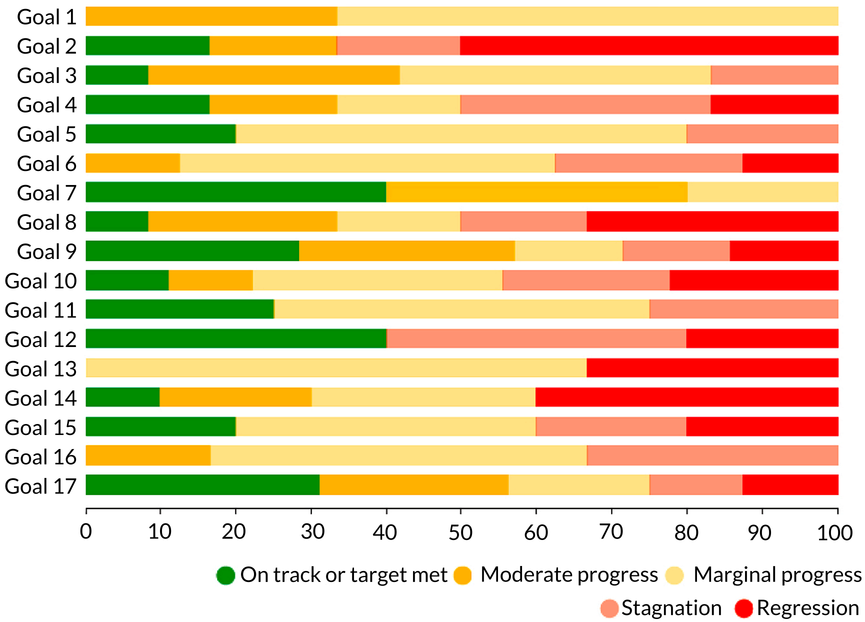

Fig. 1.3 Progress assessment for the 17 Goals based on assessed targets in 2024, %
Source: [16]

By 2030, one of the main SDG targets – SDG 6 clean water and sanitation is to achieve universal and equitable access to safe and affordable drinking water for all and to adequate and equitable sanitation, and hygiene for all and end open defecation [12, 16]. According to **Fig. 1.4**, only target 6.2 – sanitation and hygiene has a moderate progress in 2024 but sanitation needed. By 2030, one of the main SDG targets – SDG 7 affordable and clean energy is to ensure universal access to affordable, reliable and modern energy services and increase substantially the share of renewable energy in the global energy mix [12, 16]. According to **Fig. 1.4**, only target 7.a – international cooperation on energy and target 7.b – investing in energy infrastructure are on track in 2024.

By 2030, one of the main SDG targets – SDG 13 climate action is to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries and Integrate climate change measures into national policies, strategies and planning [13, 16]. According to **Fig. 1.4**, only target 13.1 – resilience and adaptive capacities has a marginal progress in 2024 and a significant acceleration needed.

6 CLEAN WATER AND SANITATION

6.1	Safe drinking water	Marginal progress, and significant acceleration needed
6.2	Access to sanitation & hygiene	Moderate progress, but acceleration needed
6.3	Water quality	Marginal progress, and significant acceleration needed
6.4	Water-use efficiency	Marginal progress, and significant acceleration needed
6.5	Trans-boundary water cooperation	Stagnation
6.6	Water-related ecosystems	Stagnation
6.a	International cooperation on water & sanitation	Regression
6.b	Participatory water & sanitation management	Marginal progress, and significant acceleration needed

7 AFFORDABLE AND CLEAN ENERGY

7.1	Access to energy services	Moderate progress, but acceleration needed
7.2	Share of renewable energy	Moderate progress, but acceleration needed
7.3	Energy efficiency	Marginal progress, and significant acceleration needed
7.a	International cooperation on energy	On track or target met
7.b	Investing in energy infrastructure	On track or target met

13 CLIMATE ACTION

13.1	Resilience & adaptive capacity	Marginal progress, and significant acceleration needed
13.2	Climate change policies	Regression
13.3	Climate change awareness	Insufficient data
13.a	UNFCCC commitments	Marginal progress, and significant acceleration needed
13.b	Climate change planning & management	Insufficient data

14 LIFE BELOW WATER

14.1	Marine pollution	Marginal progress, and significant acceleration needed
14.2	Marine & coastal ecosystems	Marginal progress, and significant acceleration needed
14.3	Ocean acidification	Regression
14.4	Sustainable fishing	Regression
14.5	Conservation of coastal & marine areas	Marginal progress, and significant acceleration needed
14.6	Fisheries subsidies	Moderate progress, but acceleration needed
14.7	Marine resources for SIDS & LDCs	Regression
14.a	Research capacity & marine technology	Regression
14.b	Small-scale artisanal fishing	On track or target met
14.c	Implementing UNCLOS	Moderate progress, but acceleration needed

15 LIFE ON LAND

15.1	Terrestrial & freshwater ecosystems	Stagnation
15.2	Sustainable forests management	Marginal progress, and significant acceleration needed
15.3	Desertification and land degradation	Regression
15.4	Conservation of mountain ecosystems	Stagnation
15.5	Loss of biodiversity	Regression
15.6	Utilization of genetic resources	On track or target met
15.7	Protected species trafficking	Insufficient data
15.8	Invasive alien species	On track or target met
15.9	Biodiversity in national & local planning	Marginal progress, and significant acceleration needed
15.a	Resources for biodiversity & ecosystems	Marginal progress, and significant acceleration needed
15.b	Resources for forest management	Marginal progress, and significant acceleration needed
15.c	Protected species trafficking (global)	Insufficient data

- On track or target met
- Moderate progress, but acceleration needed
- Marginal progress, and significant acceleration needed
- Stagnation
- Regression
- Insufficient data

Fig. 1.4 SDG progress by target in 2024
Source: compiled by the authors based on [13, 16]

By 2025, one of the main SDG targets – SDG 14 life below water is to prevent and reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution [13, 16]. According to **Fig. 1.4**, only target 14.b – small-scale artisanal fishing is on track in 2024. By 2030, one of the main SDG targets – life on land is to ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development [13, 16]. According to **Fig. 1.4**, only target 15.6 – utilization of genetic resources and target 15.7 – invasive alien species are on track in 2024.

In recent years, the delicate balance between economic development and ecological environment protection in ecologically fragile arid areas has gradually become apparent. J. Liu, X. Pei, W. Zhu, J. Jiao indicate that deep learning models effectively captured the spatiotemporal neighborhood features of land use dynamics, and CNN-GRU exhibited the highest accuracy and most accurately simulated the land use [18]. C. Paul, E. Reith, J. Salecker outline how future hybrid models could build on recent advances by inter alia an improved representation of landscape patterns, refining the theory behind decision-making, incorporating uncertainty and reducing model complexity. The scholars conclude that coupling recent developments in land-use optimization and agent-based models may help bridge gaps between modelling philosophies as well as parsimony *vs.* complexity [19].

In the sustainable use area, clarifying the complex land use impacts on ecosystem services, X. Cheng, Z. Xu, Sh. Yu, J. Peng consider that trade-off will be beneficial to watershed sustainable development, especially through scientific land use management and decision making [20]. The trade-off intensity is the strongest in farmland and forest land, and weaker in grassland and water body. Bioeconomic modelling has been positioned as an integrative approach able to deliver advice to sustainability related problems. L. Castro, F. Lechthaler see a tremendous evolution towards integrated based on multiple-goal and spatial applications. This step forward in bioeconomic modelling enables it to incorporate multiple time and spatial scales [21].

In a broader context, C. King derives a long-term dynamic growth model that endogenously links biophysical and sustainable economic variables in a stock-flow consistent manner. The two industrial sector HARMONEY (Human And Resources with MONEY) model enables exploration of interdependencies among resource extraction rate and depletion; the accumulation of population, capital, and debt; and the distribution of money flows within the sustainable economic development [22].

According O. Lytvyn, Y. Kuryliuk, A. Onyshchenko, V. Kudin, V. Parkhomenko and S. Filiuk, this once again proves that the path of sustainable development is inevitable and the concept of social responsibility should reflect rationality. Conflicting expectations of the entire set of interested parties, should be based on the principles of continuous and long-term development of business entities, with the aim of obtaining competitive advantages [23].

The complexity of the socioeconomic evolution circumscribed by the accumulation of irreversible irregularities, dissipative structures, and is a challenge with an impact on the decision-making process. In this context, sustainable development involves homeoresis and resilience under economic, ecological, and environmental constraints. Mathematical modeling in the analysis of economic, ecological, and environmental phenomena, configured in various systemic structures, allows the consideration of multiple variables, identification of conditionalities, facilitating the adoption of appropriate decisions. On these coordinates, mathematical modeling offers multiple possibilities of analysis, constituting a useful tool at the micro- and macroeconomic level.

1.4 Input-output balanced sustainable development model with consideration of environmental management processes

The aim of the study is also to develop an algorithm for synthesizing the components of a static ecological and economic mathematical model of the Leontief-Ford type of input-output (in particular, the constraint matrix and the constraint vector), the solution of which implements a given sustainable development highway.

The main issue that arises while creating a long-term plan for environmental protection and rational use of natural resources at the macroeconomic level is to justify the required amount of resources and their distribution among individual industries and regions of the country. Let's consider a model that allows to determine macroeconomic parameters of the national economy development that ensure not only economic but also environmental sustainability (**Table 1.1**). It presents a general scheme of the extended input-output one, which reflects not only flows between the sectors of conventional goods and services, but also the production and destruction of pollutants. Accordingly, the usual classification of economic activities and goods is expanded to include the names of various pollutants and measures to eliminate them.

The construction and implementation of the input-output balanced sustainable development model, based on the scheme presented in the **Fig. 1.5** allows solving a number of fundamental problems of the modern science. These problems include, in particular: development of reliable methods for predicting environmental parameters and indicators of its quality, which provide quantitative measurement of human satisfaction in a clean environment; creation of a scientifically based methodology for determining economic losses from environmental pollution; construction of a system of models of interaction between different components of natural complexes, taking into account anthropogenic factors.

Table 1.1 Input-output balanced sustainable development model with consideration of environmental management processes

PRODUCTION		Sustainable Development Goals: 6, 7, 13, 14, 15						
		Consumption						
		SOCIETY			NATURE			
		Manufacturing industries	Non-manufacturing industries	Natural resource industries	Biota	Atmosphere	Hydrosphere	Lithosphere
		1	2	3	4	5	6	7
	SOCIETY	***I quadrant*** **Economic relations** Aichi Biodiversity Targets: 3, 4, 6, 7			***II quadrant*** **Environmental impact** (pollution, radiation, vibration, noise and other types of anthropogenic impact) Aichi Biodiversity Targets: 5, 6, 8, 11, 14, 15			
1	Manufacturing industries							
2	Non-manufacturing industries							
3	Natural resource industries							
	NATURE	***III quadrant*** **Use of natural resources** Aichi Biodiversity Targets: 13, 16, 20			***IV quadrant*** **Environmental connections** Aichi Biodiversity Targets: 1, 2, 4, 10, 12, 17, 18, 19			
4	Atmosphere							
5	Atmosphere							
6	Hydrosphere							
7	Lithosphere							

Source: compiled by the authors

From a scientific point of view, it requires theoretical research to establish the conditions for the existence of a corresponding mathematical model for a given development path, in particular, with positive elements and a solution that implements it. In general, the purpose is to expand the range of research to include the solution of inverse problems.

At the same time, in accordance with the purpose, the task is also to set in the practical plane and establish the necessary (sufficient) conditions for the existence (non-existence) of a mathematical model (constraint matrix, constraint vector and variables) under given tolerances (restrictions on parameter values), the solution of which implements a given development path. The task is also to develop a procedure for evaluating organizational innovations due to the selected sustainable development priorities (according to the main line). Quantitative changes can occur in both the matrix and the constraint vector of the model.

The following objectives were set to achieve the aim:

– based on the analysis, to formulate an analog of the sustainable development highway for a static model (problem) and select basic methods and algorithms for solving it;

– develop new and improve existing approaches (based on basic methods and algorithms) to solving the problem;

– conduct a computational experiment to test the properties of the algorithms for solving the problem.

The object of the study is mathematical models of static ecological and economic processes.

The subject of the study is methods and algorithms for analyzing and solving linear systems.

1.5 Description of ecological and economic models balance in the implementation of major changes

L. Buiak, O. Bashutska, K. Pryshliak, V. Hryhorkiv, M. Hryhorkiv and V. Kobets noted that Leontief-type balance ecological and economic models play an important role in solving environmental problems. Within the framework of such models, it is possible optimally to combine groups of production and environmental industries, to consider their interconnections and interaction. At the same time, it is proposed to take into account the costs of meeting greenhouse gas emission limits in the structure of the main production sectors [6]. Structurally, ecological and economic models presented by V. Kudin, A. Onyshchenko, I. Onyshchenko can be meaningfully interpreted as cellular (block). Certain interconnections can be traced between the blocks in this matrix [11].

The balance of the economy as a form of systematic interconnection of production and consumption implies that the volume and structure of produced products and services corresponds to the volume and structure of social needs in natural and value terms. That is, in time and space, in terms of quality and quantity. This correspondence is achieved by introducing a priority MDP (making decision person) vector (highway), according to the importance of the economic and environmental components of the system's output.

V. Kudin, A. Onyshchenko, I. Onyshchenko proposed to take into account the costs of meeting greenhouse gas emission limits in the structure of the main production sectors in the form of a balance ecological and economic model:

$$\begin{cases} x_1 = A_{11}x_1 + A_{12}x_2 + Cy_2 + y_1, \\ x_2 = A_{21}x_1 + A_{22}x_2 - y_2, \end{cases} \quad (1.1)$$

where $x_1 = (x_1^1, x_2^1, \ldots, x_n^1)^T$ – a vector-column of production volumes; $x_2 = (x_1^2, x_2^2, \ldots, x_m^2)^T$ – a vector-column of destroyed pollutants' volumes; $y_1 = (y_1^1, y_2^1, \ldots, y_n^1)^T$ – a vector-column of final products' volumes; $y_2 = (y_1^2, y_2^2, \ldots, y_m^2)^T$ – a vector-column of volumes of undestroyed pollutants; $A_{11} = (a_{ij}^{11})_1^n$ – a square matrix of coefficients of direct costs of product *i* for the production of a unit of product *j*; $A_{12} = (a_{ig}^{12})_{i,g=1}^{n,m}$ – a rectangular matrix of product *i* costs per unit of pollutant destruction *g*; $A_{21} = (a_{kj}^{21})_{k,j=1}^{m,n}$ – a rectangular matrix of pollutant output *k* per unit of manufactured product *j*; $A_{22} = (a_{kg}^{22})_1^m$ – a square matrix of pollutant output *k* per unit of pollutant destruction *g*; $C = (c_{ig}^{12})_{i,g=1}^{n,m}$ – a rectangular matrix of product *i* consumption per unit of pollutant *g* emissions.

In system (1.1), it is implicitly assumed that the coefficients $a_{ij}^{11} \geq 0$, $a_{ig}^{12} \geq 0$, $a_{kj}^{21} \geq 0$, $a_{kg}^{22} \geq 0$ apply to all types of production activities (material production and pollutant elimination) the hypotheses of the basic model of inter-industry balance: the number of technological methods equals the number of types of products and each technological method produces only one type of product. In the following, it is possible to assume that matrices $A_{11}, A_{12}, A_{21}, A_{22}$ are nonnegative: $A_{11} \geq 0$, $A_{12} \geq 0$, $A_{21} \geq 0$, $A_{22} \geq 0$. The economic sense of the model (1.1) requires that all its variables are nonnegative, i.e. $x_i^1 \geq 0, x_k^2 \geq 0, y_i^1 \geq 0, y_k^2 \geq 0$.

The latter is closely related to the issue of the performance of balance models, which allows to talk about the real functioning of the production system capable of ensuring intermediate consumption, positive volumes of the final product and compliance with the established limits on greenhouse gas emissions. Achievement of their main values, i.e., the specified variables (output indicators), causes structural reorganization (changes) in individual elements, rows, columns of technological matrices of the model (1.1), as well as in the forming cells (blocks). This necessitates the development of algorithms considered by P. Samuelson for assessing the impact of changes in the blocks of the matrix structure on the solution of the system of equations [24].

The first set of equations of the proposed model reflects the economic balance – the distribution of sectoral gross output into the 'production consumption' of a primary and secondary production; a final consumption of the primary production, and costs associated with fulfilling obligations under the Paris Agreement [14]. The second set of equations reflects the physical balance of greenhouse gases as the sum of emissions caused by the activities of the main and auxiliary production and their unremoved volumes.

According to [6, 24], let's specify the model in the form

$$Au = \tilde{C}, \tag{1.2}$$

where $A = \begin{pmatrix} E_1 - A_{11} & -A_{12} \\ -A_{21} & E_2 - A_{22} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$, $u = (x_1, x_2)^T = (u_1, u_2, ..., u_m)^T$ – an m-dimensional vector; x_1, x_2 – "subvectors" u; $\tilde{C} = \begin{pmatrix} E_1 & C \\ 0 & -E_2 \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}$; E_1, E_2 – block unit matrices of the corresponding dimension; 0 – block zero matrix; Cy_2 – costs of greenhouse gas emissions (i.e., the cost of servicing greenhouse gas emissions, in particular, the cost of emission permits); $C = (c_{ig}^{12})_{i,g=1}^{n,m}$ – a rectangular matrix of product i costs per unit of pollutant g emissions.

Other variables of the system are similar in content to the corresponding variables of the model [6].

Let's also consider the system

$$\bar{A}u = \bar{C}, \tag{1.3}$$

reorganized in the way of achieving the main growth indicators (in the elements of matrices A_{11}, A_{12}, A_{21}, A_{22} and C) with respect to the system of linear algebraic equations (1.2).

In general, let's believe that the constraint vector and the constraint matrix should not "fall out" of a certain parallelepiped of variable technological constraints with their permissible value:

$$\Pi_{\bar{A}} = \left\{ \bar{A} / \bar{A}_{(H)} \le \bar{A} \le \bar{A}_{(B)} \right\}, \Pi_{\bar{C}} = \left\{ \bar{C} / \bar{C}_{(H)} \le \bar{C} \le \bar{C}_{(B)} \right\}, \Pi_u = \left\{ u / u_{(H)} \le u \le u_{(B)} \right\}.$$

A more detailed record will be used further:

$$\Pi_{\bar{a}_i} = \left\{ \bar{a}_i / a_{i(H)} \le \bar{a}_i \le a_{i_{(B)}}, i \in I \right\}, \Pi_{\bar{c}_i} = \left\{ \bar{c}_i / c_{i(H)} \le \bar{c}_i \le c_{i_{(B)}}, i \in I \right\}, \Pi_{u_i} = \left\{ u_i / u_{i(H)} \le u_i \le u_{i_{(B)}}, i \in I \right\}.$$

It should be noted that such a problem of parametric synthesis to find the structure of the system (constraint matrix and constraint vector). It is possible to assume that the solution of such a problem corresponds to the development of the main line if the solution of the problem (1.3) on the synthesized model structure coincides or is close to the given main line.

Accordingly, the statement can be as follows:

Let's form the initial model as an initial, unperturbed model of type (1.2):

$$\max Bu / Au = C,$$

$$\Pi_u = u / \bar{u}_{(H)} \le u \le \bar{u}_{(B)}.$$

It is possible to investigate the optimality of the parameters (all model parameters are unknown and bilaterally constrained) for a perturbed problem of type (1.3):

$$\max \bar{B}u / \bar{A}u = \bar{C},$$

$$\Pi_{\bar{A}} = \left\{ \bar{A} / \bar{\bar{A}}_{(H)} \le \bar{A} \le \bar{\bar{A}}_{(B)} \right\},$$

$$\left(\Pi_{\bar{a}} = \{ \bar{a}_1 / \bar{\bar{a}}_{i(H)} \le \bar{a}_i \le \bar{\bar{a}}_{i(B)} \}, i = \overline{1,m} \right),$$

$$\Pi_{\bar{C}} = \left\{ \bar{C} / \bar{\bar{C}}_{(H)} \le \bar{C} \le \bar{\bar{C}}_{(B)} \right\},$$

$$\Pi_{\bar{B}} = \left\{ \bar{B} / \bar{\bar{B}}_{(H)} \le \bar{B} \le \bar{\bar{B}}_{(B)} \right\},$$

$$\Pi_u = \left\{ u / \bar{u}_{(H)} \le u \le \bar{u}_{(B)} \right\}.$$

By applying, for instance, the penalty function method, problem (1.3) of conditional optimization is reduced to the problem of unconditional optimization of the function for a minimum under bilateral constraints on the parameters:

$$\min \left\{ -\bar{B}u + \sum_{j=1}^{m} M_i \times \left| \bar{a}_i u - \bar{c}_i \right| \right\},$$

$$\Pi_{\bar{A}} = \left\{ \bar{A} / \bar{\bar{A}}_{(H)} \le \bar{A} \le \bar{\bar{A}}_{(B)} \right\},$$

$$\Pi_{\bar{a}} = \left\{ \bar{a}_1 / \bar{\bar{a}}_{i(H)} \le \bar{a}_i \le \bar{\bar{a}}_{i(B)} \right\}, i = \overline{1,m},$$

$$\Pi_{\bar{C}} = \left\{ \bar{C} / \bar{\bar{C}}_{(H)} \le \bar{C} \le \bar{\bar{C}}_{(B)}, M_i, i = \overline{1,m} \right\},$$

$$\Pi_{\bar{B}} = \left\{ \bar{B} / \bar{\bar{B}}_{(H)} \le \bar{B} \le \bar{\bar{B}}_{(B)} \right\},$$

$$\Pi_u = \left\{ u / \bar{u}_{(H)} \le u \le \bar{u}_{(B)} \right\}.$$

Let's find the values of the parameters $\bar{A}$, u, E_1, $\bar{B}$ (present them as the results) that optimize the objective function, explore different dimensions of the problem. While studying such a problem (reducing it to discrete programming), for instance, using a genetic algorithm, the problem becomes high-dimensional. If to discretize each variable i, $(i=\overline{1,k_0})$ by values from the interval n_i of the problem, then such a problem leads to an overrun of options $P=\prod_{i=1}^{k_0} n_i$. As a result, it is possible to find an approximate solution (acceptable or invalid). To ease the burden of the large dimensionality of such a problem, it seems advisable to take measures at the stage of pre-optimization (analysis of the problem's solvability) and take into account the technological features of a particular problem at the modeling stage.

1.6 Hypotheses, assumptions and simplifications of a static ecological and economic model

The formulation of the inverse problem (to the classical direct one) of finding a mathematical model structure, the solution of which is the desired development highway of a static ecological and economic model, requires some additional refinements.

In particular, to outline the limitations in the construction of a given development highway:

A. The principle of "small steps" of exit.

The development highway can be considered in a global and local context. The global context defines the pipeline as a promising final benchmark for the state of the system as a result of organizational innovations and changes in general. It can be considered the result of a series of local step changes over a certain period of time. The global resultant vector is mathematically the sum of local trunk vectors of desired system states.

The local context focuses on the formation of a change vector and finding reasonable reorganization measures to refine the model within a limited period of time, taking into account the technological capabilities of the system to change.

B. The principle of local ("small") changes in the solution and the highway vector.

The parallelepiped of possible changes and the length of the change vector k_0 along the main line causing changes in the model, both in the technological matrix and in the constraint vector (blocks of technological matrices) are assumed to be local. This is due to the fact that the boundaries of the variables and the gradient can be considered as the result of a certain linearization of the nonlinear problem and the correctness of the nonlinearity representation by a linear approximation can be correct only in the neighborhood (local). Through the latter, let's extract y_1 and y_2, C.

C. The principle of local ("small") changes in model elements.

In terms of manufacturability, structural reorganization should be carried out within certain limited time frames, carried out evolutionarily, accompanied by small quantitative changes, taking into account the technological capabilities of the system.

D. The principle of correctness and conditionality of the system in case of changes in the model elements.

It is known that for correct, well-conditioned linear systems in modeling, small changes in the model correspond to small changes in the initial parameters of the system solutions. For instance, the conditionality number $M_A = \|A\| \times \|A^{-1}\|$ relates changes in the constraint vector in the model and the solutions of the problem.

While working with incorrect systems, disproportionate changes in the system are observed. Moreover, small quantitative changes in the model can be accompanied by significant qualitative changes in the output parameters. The nondegeneracy of the constraint matrix is violated, the rank of the technological matrix "falls", etc., and the uniqueness of the solution is not met. The correction (reorganization of the system) of constraints is considered as a multi-stage procedure of small changes, which is caused by the corresponding small changes in the main line.

It is necessary (provided that the system is correct) that small changes in the local vector of the development highway will cause small changes in the model elements such as the technological matrix, the constraint vector.

E. The principle of ergativity.

It is assumed that there is a decision-maker (DM) in the decision-making loop of the ecological and economic system.

The DM forms the resulting global development highway and its local components at different stages. The resultant highway (as a vector) is the sum of local highway vectors at the reorganization steps. The reorganization structure corresponding to the local trunk vector is determined by one of the mathematical methods (e.g., method of basis matrices).

The DM also forms the neighborhood of the solution change in the neighborhood (parallelepiped). Subsequently, mathematical procedures form an adequate length of the trunk vector. The DM can define the backbone vector as a certain cone with the points in the current state of the system. The DM can also eliminate ambiguities in the description of individual components.

F. The principle of "proximity" of individual elements of the model and the development pipeline.

It is evident that, the smaller the difference (proximity) of the main lines to, for instance, the product (cone of tolerance), the smaller the changes in the inverse matrix when replacing the column-item of the inverse matrix with the vector-column of the main line. If the system is correct, small changes in the inverse matrix will cause small changes in the direct matrix, i.e., the constraint matrix of model (1.2).

If the equation $u=u_0+k_0e_k$ of the cone product (acceptable), and is the equation $\bar{u}=u_0+k_0e_l$ of the highway (desired), then it is possible to write $\bar{u}-u=k_0(e_l-e_k)$, $\|\bar{u}-u\|=|k_0|\|(e_l-e_k)\|$. That is, for "small differences", small deviations of the solutions and vectors of the generating equation from the main line are associated. The "small" deviations of the product and the backbone vector during the substitution operation in the inverse matrix of the vector-column of the product vector with the backbone vector will have small changes. If the system is correct, it will cause small changes in the direct matrix, as well as their norms. The latter, the direct matrix, is the forming matrix of system (1.2). With "good" conditioning (the product of the norms of the new direct and inverse matrices will be a small number).

1.7 Technology of reorganization in a static ecological and economic model to achieve the values of main indicators

Developing the reorganization technology, the method of basis matrices (MBM) was applied. This is a method of the type of simplex-methods which is aimed at analyzing and solving the above problems, both direct and inverse. It should be noted that these are primarily problems of linear systems analysis, in particular, linear algebraic equation system (LAES), and are basic ones mentioned by V. Kudin, V. Onotskyi, A. Al-Ammouri, L. Shkvarchuk in conducting more complex studies and generalizations. As a rule, modern computers use standard types of integers which size does not exceed 64 bytes [10].

This hardware limitation was overcome by software, namely, by developing our own data type in the form of a special Longnum library in C++ using the Standard Template Library (STL). The software implementation was developed to perform calculations using the MBM and Gauss, i.e., long arithmetic for models with rational elements was used. The algorithms and computer implementation of Gauss-type methods and artificial basis matrices (a variant of the basis matrix method) in Matlab and Visual C++ environments using the technology of accurate computation of method elements, primarily for ill-conditioned systems of different dimensions, are proposed.

It should be noted that the MBM has been thoroughly tested (as a "solver" of a system of linear algebraic equations), in particular, for geohydrodynamics problems. In particular, procedures for finding and refining the solution for models of geohydrodynamic problems were developed on the basis of the MBM; software for computational experimentation was developed for typical models; the reliability was checked, and the main parameters (solution accuracy, solution time) of the MBM computational results were compared with the Gauss, SVD, and Greville methods depending on the number of conditionality.

The aforementioned problems are characterized by poor conditionality, bad completeness of the constraint matrix (sparsity), large dimensionality, and certain structural features of the constraint matrix. A number of these properties are also inherent in mathematical models (1.2) and (1.3), both for forward and inverse problems.

Nowadays the study of MBM algorithms has been neglected in the analysis of inverse problems. Thus, the effect of the implementation of the desired master values (the vector of values of the components of the output parameters) on the structural properties of the matrix model (in a linear system) on the various components of the model. For the direct problem, such studies (to analyze the impact of such changes in the model elements) on the properties of a linear system (without solving the problem) were conducted by V. Kudin, A. Onyshchenko, I. Onyshchenko – element, row, column of the constraint matrix, etc. [11].

The scheme of the method of artificial basis matrices is a specification of the MBM to analyze the properties of linear systems of equations and inequalities, in particular, with a square constraint matrix. The basis of the proposed method of artificial basis matrices and its corresponding algorithms is the idea of a basis matrix formed by linearly independent rows of the constraint matrix. The process of iterative splicing (replacement) of the constraints of the auxiliary system with the relaxed constraints of the main system is carried out.

The square matrix mentioned by V. Kudin, V. Onotskyi, A. Al-Ammouri, L. Shkvarchuk (in general, a submatrix) $A_b = A = \|a_{ij}\|$, $i=\overline{1,m}$, $j=\overline{1,m}$, consisting of m linearly independent row-normals $a_i = \left[a_{i1}, a_{i2}, ..., a_{im}\right]$, $i=\overline{1,m}$, will be called an artificial basis, and a solution $u_0 = (u_{01}, u_{02}, ..., u_{0m})^T$ of the corresponding system of equations $A_b u = C^0$, where $C^0 = (c_1, c_2, ..., c_m)^T$ is an artificial basis [10].

Definition 1. In the general case, let's understand the highway as a cone formed by the tip (solution vector) and the vector (set of solution vectors) with nonnegative components, which indicates the "desired membership set" of solutions (values of the "system output") of the directionally reconfigured ecological and economic system (as a solution to the inverse problem).

Definition 2. The reconfigured system is a mathematical model of the form (1.3) obtained as a result of the implementation of the main guidelines for sustainable growth at time t (step of change).

Definition 3. In this formulation, the mainline is defined by the vector $u = u_0 + t \times e_{.l}$, $t > 0$, where $e_{.l}$ is the mainline vector. It is assumed that the backbone vector should not "fall out" of the parallelepiped of variables centered at the point u_0 with its changes

$$\Pi_{u_0} = \{u = (u_1, u_2, \ldots u_m)^T / u_{0i(H)} \leq u_{0i} \leq u_{0i(B)}, i \in I\}.$$

Let's suppose, e_{ri} are the elements of the matrix $A^{-1} = \|e_{ij}\|$, $i = \overline{1,m}$, $j = \overline{1,m}$, composed of m linearly independent column vectors $e_j = (e_{1j}, e_{2j}, ..., e_{mj})$, $j = \overline{1,m}$ inverse to $A = A_b$; $\alpha_{.i} = (\alpha_{i1}, \alpha_{i2}, ..., \alpha_{mj})$, $j = \overline{1,m}$ is the development vector of the constraint vector α_i along the rows of the basis matrix $A = A_b$ $(\alpha_{i.} = \alpha_i \times A^{-1})$; $\beta_{.l} = (\beta_{l1}, \beta_{l2}, ..., \beta_{lm})$ – column expansion vector of the backbone vector $e_{.l} = (e_{1l}, e_{2l}, ..., e_{ml})$ along the columns of the matrix A^{-1} $(\beta_{.l} = A \times e_{.l})$; $\Delta_r = \alpha_r u_0 - c_r A^{-1}$ $(\beta_{.l} = A \times e_{.l})$; $\Delta_r = \alpha_r u_0 - c_r$ – the invariance of the r constraint (1.1) at the vertex u_0. All the introduced elements in the new basis matrix $\overline{A}_b$, which differ from A_b by one row, will be marked with a dash from above. The ideology of the simplex methods (including the method of basis matrices) establishes the relations between the direct and inverse matrices when replacing one row (column) with another, subject to the condition of non-degeneracy (support) of the newly formed matrices. It should be noted that the category (names) of the direct and inverse matrices are relative in the context of a particular application. In particular, for the direct and inverse matrices, the following relations hold

$$A_b \times A_b^{-1} = E\left(\left(A_b^{-1}\right)^T \times A_b^T\right) = E.$$

In the left formula, let's consider A_b to be a direct matrix and the second one to be an inverse matrix to it and in the second formula (in parentheses), $(A_b^{-1})^T$ is a direct matrix and the second one A_b^T an inverse matrix (as if it were the other way around). Here, the matrix where the simplex iteration of row (column) substitution is performed is a direct matrix, and the matrix determined as a result of the substitution will be the inverse (to this direct matrix).

According to Theorem 1 (numerical mathematics), the relationship between the coefficients of the development of the constraint normals, elements of the inverse matrices, basis solutions, and constraint disjunctions in two adjacent basis matrices is established. A scheme for determining the rank of the system's constraint matrix and the solution of the system of equations can be built based on them by successive changes in the basis matrices and the corresponding artificial solutions.

It is known that the properties of a LAES of type (1.1) have connections with the corresponding SLAN (system of linear algebraic inequalities). Namely

$$Au \leq \overline{C}. \tag{1.4}$$

The linear algebraic inequality system (LAIS) (1.4) is formed by the intersection of nonpositive half-spaces generated by the hyperplanes of constraints (1.2). The influence of changes in the model is usually studied through a direct constraint matrix in practical problem formulations (e.g., the problem of the influence of perturbations in the elements of the constraint matrix on the properties of the solution). However, it happens that the problem is posed vice versa, according to the given properties of the problem solution, it is necessary to recreate a model (reconfigure) that will have the given solution properties. In such cases, the main emphasis of analyzing the impact of changes on the solution is studying the properties of the already inverse matrix.

For instance, there is a desired vector of a new solution that has certain properties (in relations) with the cone components. In this case, it is natural to "start from" the structure of the inverse matrix (columnar) in the analysis. If to represent the direct and inverse matrices in a transposed form, it follows that the columnar matrix of the derivatives (inverse) becomes a direct (ordinal) matrix. The analysis of changes in such a matrix can be carried out on the basis of the ordinal strategy of the MBM, in particular, to determine the properties of the inverse matrix to it (i.e., the original model).

It is evident that the smaller the difference (proximity) of the trunk vector to the product vector, the smaller the changes in the inverse matrix when replacing the column – the product of the inverse matrix with the trunk vector. Assuming the correctness of the system, small changes in the inverse matrix will cause small changes in the direct matrix, i.e., the constraint matrix of the model (reconfigured system).

1.8 Conception of SDGs and algorithm for building directed changes

As for the basic statements and algorithm for building directed changes (development highways) based on the given initial benchmarks, for solving the inverse problem, let's further apply the provisions of the method of basis matrices and its algorithm, in particular, the formulas for recalculating the elements of the method. Assuming that the direct matrix of the simplex iteration of the basis matrix method is $(A_b^{-1})^T$, and the inverse matrix is A_b^T $((A_b^{-1})^T \times A_b^T) = E)$ when the k position of the direct matrix $e_{.l}$ (already a row) is replaced by the main line $e_{.l}$ (whose development vector is already $\beta_{.l} = (\beta_{1l}, \beta_{2l}, ..., \beta_{ml})$, $\beta_{kl} \neq 0$ (support condition), the columns of the newly formed inverse matrix $\bar{A}_b^T$ are given by the relations

$$\bar{a}_k^{-T} = \frac{a_k^T}{\beta_{kl}}, \bar{a}_k^{-T} = a_{i.}^T - \frac{a_{k.}^T}{\beta_{kl}} \beta_{il}, \beta_{kl} \neq 0, i \neq k, i \in I. \tag{1.5}$$

For the resulting matrices, either $\overline{(A_b^{-1})^T} \times \bar{A}_b^T = E$ or $\bar{A}_b \times \bar{A}_b^{-1} = E$ will be performed. In this case, the iteration is performed by replacing the product vector, for instance, with the backbone vector.

The closeness of the product and backbone vectors (angle γ) can be "measured" by the ratio

$$\cos(\overbrace{e_k, e_l}^{\gamma}) = \frac{(e_{.k}^T, e_{.l}^T)}{\left\| e_{.k}^T \right\| \times \left\| e_{.l}^T \right\|}, \underbrace{\min}_{i \in I} \cos(\overbrace{e_{.k}, e_{.l}}^{\gamma}), k = \underbrace{\operatorname{argmin}}_{i \in I} |\cos(\overbrace{e_{.k}, e_{.l}}^{\gamma})|,$$

where the index k is the column number of the candidate vector to be replaced by the backbone vector.

It is possible to write that $\bar{u} - u = k_0(e_{.l} - e_{.k}), ||\bar{u} - u|| = |k_0|||(e_{.l} - e_{.k})||$. It follows that for "small differences", "small" deviations of the solutions and vectors of the product from the backbone are associated with "large differences" and for "large differences", large deviations are associated with the backbone. "Small" deviations of the product and the backbone vector in the case of the replacement operation in the inverse matrix of the product vector by the backbone vector will "give" small changes and vice versa. If the system is correct, this will cause small changes in the direct matrix, as well as their norms (the reconfigured system). The latter (direct matrix) is the forming matrix of the system (1.3). In particular, with "good" conditionality (the product of the new direct and inverse matrices will be a small number). It is not difficult to see that the recalculation of the elements of the inverse matrix (already in the inverse problem) corresponds to one iteration of the MBM, i.e., to the solution when the backbone vector is introduced into the basis matrix.

For each constraint (1.3), let's introduce quantities

$$L_i = \left[L_{i(H)}, L_{i(B)} \right], R_i = \left[c_{i(H)}, c_{i(B)} \right], \bar{u} = u_0 + k_0 \times e_{.l},$$

where

$$L_{i(H)} = \min\left\{ (a_i, u) / a_{i(H)} \le a_i \le a_{i(B)}, u_{(H)} \le u \le u_{(B)}, i \in I \right\},$$

$$L_{i(B)} = \max\left\{ (a_i, u) / a_{i(H)} \le a_i \le a_{i(B)}, u_{(H)} \le u \le u_{(B)}, i \in I \right\}.$$

Proposition 1. A sufficient condition for $\bar{u} = \Pi_u$ the absence of the corresponding matrix and constraint vector from the set of tolerances ($A \in \Pi_{\bar{A}}$, $C \in \Pi_{\bar{C}}$) for a given developmental path is the fulfillment of the following condition $\exists i_0 \in I$, $L_{i_0} \cap R_{i_0} = \varnothing$.

Proof. The introduced values ($\forall i \in I, L_i, R_i$) define, respectively, the region of values of the left side of each equation and the right side of (1.3). The existence of at least one equation from the system for which the intersection of the regions of values is an empty set indicates the insolvability of the equation and the entire system of equations. That is, there will be no matrix or vector of constraints forming a system of type (1.3) whose solution corresponds to the developmental highway.

Proposition 2. A necessary condition for $\bar{u} \in \Pi_u$ the existence of a matrix and a vector of constraints from the set of tolerances ($A \in \Pi_{\bar{A}}, C \in \Pi_{\bar{C}}$) for a given developmental mainline is the fulfillment of the condition $\forall i \in I, L_i \cap R_i \neq \varnothing$.

Proof. The existence of a non-empty intersection of the regions of values for all equations from the system (for the previously introduced value $\forall i \in I, L_i, R_i$ indicates the solvability of the equation and the entire system of equations as a whole. That is, there is room to continue searching for the matrix and constraint vector forming a system of type (1.3), the solution of which will correspond to the development highway.

In general, the fulfillment of the performance conditions (model properties) implies the positivity of the model elements when transformed to the form (1.2). If the condition of preserving the positivity of the model elements when transformed to the system (1.2) is met, a number of properties are established for such a model.

Proposition 3. A necessary condition for preserving the positivity of the elements of the reconfigured model (1.3) under transformation in the direction of the trunk $e_{.l}$ (which development vector $\beta_{.l} = (\beta_{1l}, \beta_{2l}, ..., \beta_{ml})$ is the existence of an index k such that $\beta_{kl} > 0$.

Proof. According to the formula (for k) of the "new" column $a_k^{-T} = a_k^T / \beta_{kl} > 0$ when the condition $\beta_{kl} > 0$ is fulfilled. Since, $a_k^T > 0$ under the assumption of the positivity of the elements of the model (1.2).

Corollary 1. A sufficient condition for the absence of a reconfigured model (1.3) with positive elements when transformed in the direction of the trunk $e_{.l}$ (which development vector $\beta_{.l} = (\beta_{1l}, \beta_{2l}, ..., \beta_{ml})$ is that $\beta_{il} < 0, i = \overline{1,m}$.

Proof. According to the transformation formula, if the k column is chosen arbitrarily, the "new" column (leading) will be $a_k^{-T} = a_k^T / \beta_{lk} < 0$ when the condition $\beta_{kl} < 0$, $a_k > 0$ is fulfilled. Since, $a_{k.}^T > 0$ under the assumption of the positivity of the elements of the initial model (1.2).

Corollary 2. A sufficient condition for the reconfigured model (1.3) to retain positive elements when transformed in the direction of the trunk line $e_{.l}$ (whose development vector $\beta_{.l} = (\beta_{1l}, \beta_{2l}, ..., \beta_{ml})$ is the existence of an index k such that $\beta_{kl} > 0$ and $\beta_{il} < 0, i = \overline{1,m}\,(i \neq k)$.

Next, let's present an algorithm for constructing a system of type (1.2) for a given system, taking into account the bilateral constraints on variables and without taking into account the restriction on the positivity of the elements of the model of the original reconfigured system as a result of transformations caused by the main changes, i.e., solving the inverse problem.

Algorithm.

Preparatory step. Let u_0, $A = A_b$ (its rows a_i, $i=\overline{1,m}$, A_b^{-1} (its columns $e_{.i}$, $i=\overline{1,m}$ for LAES (1.2) representing the ecological and economic model) be known. Let's form the boundaries of permissible changes in the initial parameters of the model as a parallelepiped of the form

$$\Pi_{u_0} = \left\{ u = (u_1, u_2, \ldots u_m)^T / u_{0i(H)} \le u_{0i} \le u_{0i(B)}, i \in I \right\}, u_0 \in \Pi_{u_0}.$$

Step 1. Decision makers (DMs) determine the column vector of the highway – $e_{.l}$, i.e. the desired vectors of changes in the initial system of parameters in the form of the vector $u = u_0 + t \times e_{.l}, t > 0$.

Step 2. Find the development of $e_{.l}$ – the column vector of the main line by columns A_b^{-1} according to the ratios ($\beta_{.l} = A \times e_{.l}$).

Step 3. Check the support condition $\beta_{kl} \ne 0$ when performing the operation of replacing column k ($e_{.k}$) with the trunk vector $e_{.l}$ in the matrix A_b^{-1} (form $\overline{(A_b^{-1})^T}$). This is analogous to the operation of replacing the row k ($e_{.k}^T$) with the backbone vector-row (transposed ($e_{.l}^T$)) in the matrix, forming $\overline{(A_b^{-1})^T}$.

Step 4. Form the columns of the newly formed (inverse of $\overline{A_b^T}$!) matrix, i.e., the matrix $\bar{A}$ by the ratios

$$\bar{a}_k^T = \frac{a_{k.}^T}{\beta_{kl}}, \bar{a}_{i.}^T = a_{i.}^T - \frac{a_{k.}^T}{\beta_{kl}} \beta_{il}, \beta_{kl} \ne 0, i \ne k, i \in I.$$

Step 5. Find the values $k_0 = \min\limits_{i \in I} \left(\frac{u_{i(B)} - u_{i(H)}}{2} \right)$ and form $\bar{u} = u_0 + k_0 \times e_{.l}$.

Step 6. Putting the values $\bar{C} = \bar{A}(u_0 + k_0 e_{.l})$.

The final step. Determining the amount of changes in the model elements during the reorganization of the system using the formulas

$$C' = \bar{C} - C, A' = \bar{A} - A.$$

Steps 1–4 applying the MBM relations (one iteration) to the inverse problem – finding the constraint matrix of the corresponding development pipeline.

Step 5 adjusting the step size of the backbone vector in accordance with the constraints on the variables.

Step 6 is the formation of a constraint vector corresponding to the development pipeline.

At the final step, let's determine the magnitude of changes (deviations) in the newly formed structure (matrix and constraint vector) that implement the development pipeline relative to the initial values of the system elements.

The above steps generally define the procedure for solving the inverse problem. The proposed algorithm finds a matrix and a vector of constraints, i.e., the components of the mathematical model whose solution is realized by the development highway. The core of the algorithm of the inverse problem (construction of the development highway) is the iteration of the additional solution (refinement) of the MBM.

The inverse problem (construction of a static problem development highway) is reduced to the use of linear systems tools (direct problems) that have been tested on other classes of problems. The computational complexity of the steps of the procedure for solving the inverse problem (building a static problem development highway) is correlated with the iteration of the MBM (forward problem).

Hence, a sustainable development involves improving of the quality of life of the entire world's population without increasing the use of natural resources to a level that exceeds the capacity of the Earth as an ecological system. Efforts for creating a sustainable way of life involve a comprehensive approach to activities in three key areas (**Fig. 1.5**), such as:

– economic growth and equity – applying a comprehensive approach to stimulate long-term economic growth;

– conservation of natural resources and environmental protection – finding economically viable solutions to the problem of reducing resource consumption and stopping environmental pollution;

– social development – meeting the needs of people for work, food, education, energy, healthcare, ensuring cultural and social diversity and the rights of workers, providing opportunities for all members of society to participate in decision-making that affects their future.

In our opinion, the economic approach to the concept involves the optimal use of limited resources and the use of environmentally friendly, nature conservation and energy saving technologies, as well as technologies for recycling and emission destruction. However, when deciding what kind of capital should be preserved and to what extent different types of capital are interchangeable, as well as when valuing assets, especially environmental resources, there are problems of proper interpretation and calculation.

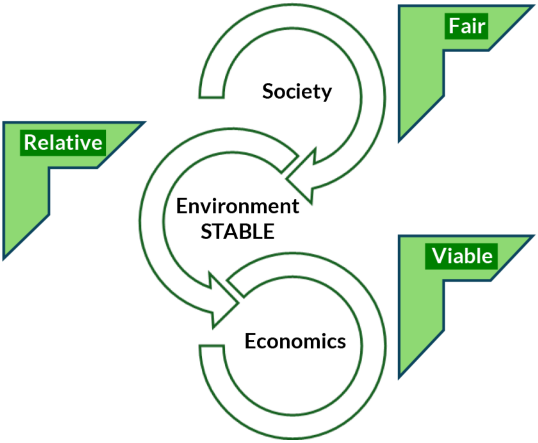

Fig. 1.5 Conception of Sustainable Development Goals
Source: compiled by the authors

Two types of sustainability have emerged: 1) weak, when it comes to time-decreasing natural and productive capital, and 2) strong, when, in addition to time-decreasing natural capital and a portion of the profit from the sale of non-renewable resources, it is necessary to increase the value of renewable natural capital.

1.9 Conclusions

It is established that the solution of the inverse problem of finding the structure of a mathematical model (for a given developmental path) in terms of computational volume corresponds to one iteration of the MBM solution. A number of statements are substantiated; in particular, the conditions for the existence of the corresponding matrix, constraint vector and their positivity for the development mainline. The solution of the master problem in the course of modeling provides feedback in the system. This is important for analyzing the impact of different "scenarios" of sustainable development (the main line) on the constraint matrix and the constraint vector of the reconfigured ecological and economic model. An algorithm is proposed, which in essence is an iterative procedure for refining the initial model by conducting similar iterations of the MBM. That is, finding a reconfigured (directionally changed) system as a result of the impact of mainstream changes to the inverse problem.

Since it has been established that the MBM can be applied to both the direct and inverse problems, the results of the experiments and the comparison of computational schemes for linear systems conducted earlier can be taken into account in further applications. The computational experiment on the model example shows that the main computational load of the algorithm is the iteration of the MBM solving.

The social component of sustainable development is human-centered and aims to maintain the stability of social and cultural systems. An important aspect of this approach is the fair distribution of benefits. The society will have to create a more efficient decision-making system to achieve sustainable development. It is important to get not only internal but also intergenerational justice. From an environmental perspective, sustainable development must ensure the integrity of biological and physical natural systems. Of particular importance it is the viability of ecosystems, which the global stability of the entire biosphere depends on. The particular attention is paid to the preservation of self-healing and dynamic adaptation of such systems to changes, rather than preserving them in some ideal static state.

Reconciling these different perspectives and implementing specific measures is a rather complex task, as all three elements of sustainable development must be considered in a balanced manner. The mechanisms of interaction between these three concepts are also important. The economic and social elements interact to generate new challenges such as achieving equity, social guarantees, the right to work, and providing assistance to the poor. The interplay of the economic and environmental elements gives rise to new considerations regarding the valuation and inclusion of external environmental impacts and efficient environmental management in economic reporting. The linkage of social and environmental elements arouses interest in such issues as respect for the rights of future generations, public participation in decision-making, and control over climate change.

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CHAPTER 2

Cost assessment of climate change impacts on a railway company

Valerii Samsonkin
Iuliia Bulgakova
Oksana Yurchenko

Abstract

The frequency and severity of climate change impacts on the railway sector are steadily increasing. As a result, railway companies are currently in the process of developing resilience strategies to adapt to these challenges. A key element of this process is the assessment of climate-related risks and the adoption of effective risks mitigation measures. This chapter focuses on the economic dimension of climate resilience by evaluating the financial costs incurred by a railway company due to climate change impacts. Understanding these costs is crucial for assessing the scale of climate risks and for determining the economic efficiency of risk mitigation measures. The chapter identifies, systematizes, and classifies various categories of climate-induced costs borne by railway operators. In addition, it proposes a cost assessment methodology that is particularly suitable for practical application, drawing on a comparative analysis of the best international practices. This approach contributes to informed decision-making in climate adaptation planning for the railway sector.

Keywords

Climate change, railway company, decision making, climate mitigation measures, economic impact, risks assessment, transport-environment interaction.

2.1 Introduction

Climate change has already had significant adverse effects on railway systems worldwide, with projections indicating that these risks will remain high and possibly escalate in the future. According to data from the European Union

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Agency for Railways (ERA), between 2007 and 2023, National Investigation Bodies (NIBs) reported 100 railway incidents directly or indirectly attributed to climatic factors. Weather-related hazards such as heavy snowfall and icing, strong winds, intense rainfall, and fog frequently contribute to train derailments, collisions, and level crossing incidents. Additionally, railway infrastructure is especially vulnerable to flooding – both riverine and coastal – heatwaves, cold spells, and wildfires, although it tends to be less sensitive to windstorms. The recovery period following major flood events can exceed four years, underscoring the prolonged impact of extreme weather events on rail network functionality and resilience [1, 2].

A substantial body of research has addressed the assessment of climate risks at both micro and macro levels within the railway sector, detailing the climatic factors involved, their consequences, and the extent of their impact [1, 3]. There is also extensive documentation of global experience in implementing climate mitigation measures, often with particular attention to regional climatic characteristics [1, 4, 5]. However, despite this knowledge, there remains no comprehensive system of indicators to effectively assess the costs railway companies incur due to the consequences of climate change.

The frequency and severity of climate-related impacts on railways continue to rise, prompting railway operators to develop resilience strategies aimed at adapting to these emerging challenges. Central to these efforts is the systematic assessment of climate risks and the implementation of effective mitigation measures. This chapter focuses on the economic dimension of climate resilience by evaluating the financial costs that railway companies bear because of climate change impacts. Understanding these costs is essential not only for quantifying the scale of climate risks but also for assessing the economic efficiency of various risk mitigation approaches.

In this context, the chapter identifies, systematizes, and classifies different categories of climate-induced costs faced by railway operators. Building upon a comparative analysis of the best international practices, it proposes a practical methodology for cost assessment tailored to the railway sector. This methodology aims to support informed decision-making in climate adaptation planning.

Effective decision-making regarding climate mitigation in railways involves a multi-stage process: beginning with the identification and evaluation of risks and vulnerabilities, followed by the consideration of potential mitigation options, and concluding with the selection of the most effective and feasible strategies (**Fig. 2.1**). This structured approach is critical to enhancing the resilience and sustainability of railway operations in the face of ongoing climatic changes.

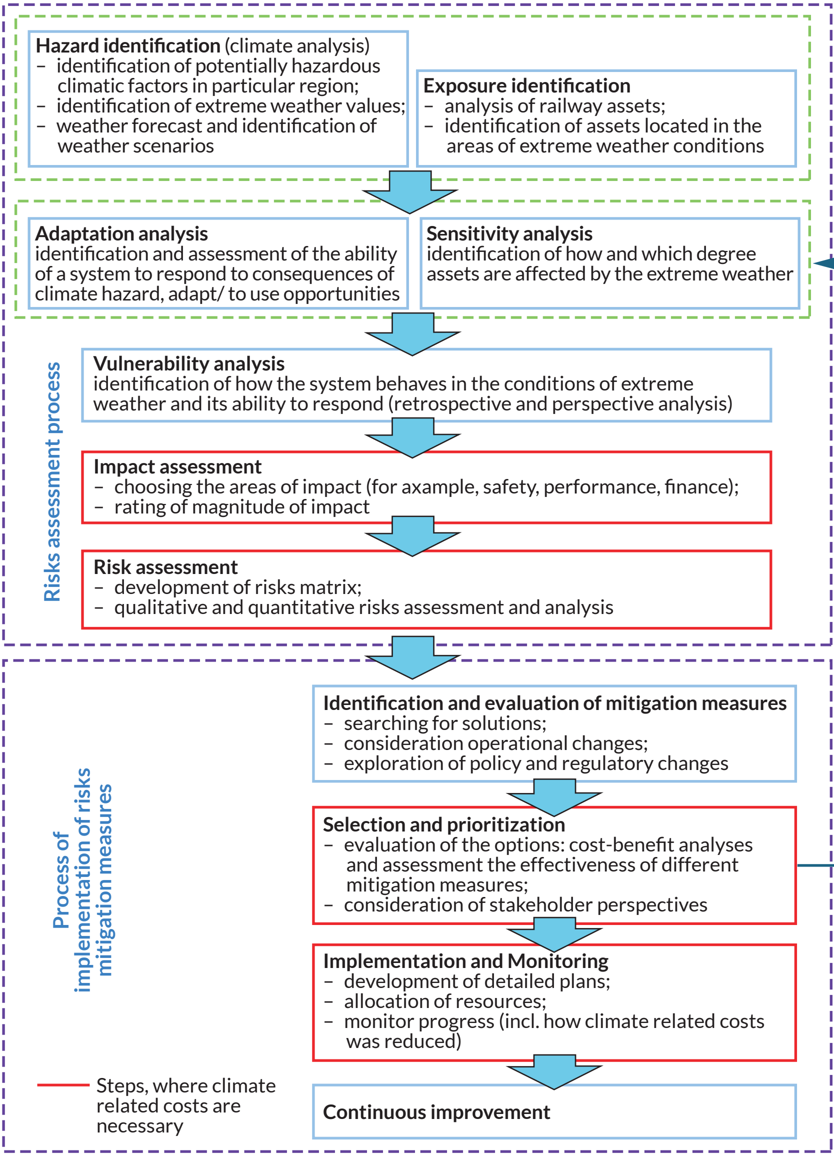

Fig. 2.1 Decision making on climate related risks mitigation measures
Source: authors' development based on [3, 6]

Estimation of climate impact costs is necessary at the following stages of the decision-making process for climate-related risk mitigation measures:

– *impact assessment*: evaluating the extent of climate risk impact on the company's economic performance;

– *risk assessment*: quantitative evaluation of risks expressed in monetary terms;

– *selection and prioritization of risk mitigation measures*: conducting cost-benefit analysis;

– *implementation and monitoring*: assessing the changes in climate impact costs after the implementation of risk mitigation measures.

Based on the analysis of railways worldwide on the climate risks assessment, resilience strategies, climate risks mitigation and adaptation measure the following climate related costs which is taken by the railway company are defined (**Table 2.1**). The costs are classified as direct and indirect.

Table 2.1 Climate related cost of railway company

No.	Cost category	Short description	Direct/ indirect	Methods of calculation
1	2	3	4	5
1	Costs of incidents	General costs related to accidents and emergency situations, including those influenced by climate factors	Mixed	Case analysis, statistical data, expert evaluation
1.1	Costs of injuries and fatalities	Includes medical expenses, production losses, human life valuation, and administrative costs	Direct, Indirect	Actual costs, willingness to pay (WTP)
1.2	Cost of train delays (due to accidents)	Includes delays of locomotives and carriages, extra fuel/electricity consumption, crew overtime, compensations, and penalties	Direct	Actual costs
1.3	Damage costs	Environmental and infrastructure damage caused by accidents or extreme weather	Direct	Actual renovation/recovery costs to initial conditions
1.4	Incident investigation costs	Additional investigation tools and methods applied due to climate-related events	Indirect	Actual costs
2	Maintenance costs	Additional maintenance requirements resulting from extreme weather events	Direct	Life cycle cost analysis (LCCA), actual costs
3	Infrastructure adaptation costs	Investments aimed at increasing climate resilience of railway infrastructure (bridges, tracks, drainage systems)	Direct	Forecasted investment, cost-benefit analysis

Continuation of Table 2.1

1	2	3	4	5
4	Cost of train delays (non-incident causes)	Costs of delays not caused by accidents (e.g., weather disruptions, infrastructure issues)	Direct	Actual costs, time loss valuation
5	Costs related to passenger behavior changes	Costs associated with modal shift caused by climate change (e.g., switch from rail to road or vice versa)	Indirect	Demand modeling, investment analysis, income/ expenditure forecasting
6	Costs of reduced worker productivity	Includes loss of wages, medical care, overtime, replacement and training, and reduced performance due to extreme temperatures	Direct, Indirect	Actual costs, labor statistics, productivity models
7	Costs of reputational loss	Includes stock price drop, customer attrition, internal disruption, changes in partnerships, legal consequences	Indirect	Actual costs, event study analysis, market correlation models

Source: authors' development

Direct costs – costs, which railway company can expect to pay out of pocket, immediately after the risk event occurrence. These costs are usually well-dated and easy to keep track of.

Indirect costs – secondary expenses railway company incurs following a risk event occurrence. They accumulate over time. Because of this, Indirect costs can be harder to measure but they generally exceed direct costs.

2.2 Costs of incidents

The variation in the number of weather-related railway accidents over the examined period does not reveal a consistent or discernible trend. While a certain number of such occurrences are investigated annually, the data does not indicate a clear upward trajectory. This is likely influenced by the fact that, in many cases, there is no mandatory requirement to initiate a formal investigation.

NIBs obligatory investigates and report to the ERA on *significant accidents*, which means any train collision or derailment of trains resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other accident with the same consequences which has an obvious impact on railway safety regulation or the management of safety; *extensive damage* means damage that can be immediately assessed by the investigating body to cost at least 2 million EUR in total [7].

Thus, the dataset available in the ERAIL database constitutes only a partial representation of all accidents, reflecting a selected sample rather than the complete scope of incidents.

It is also important to note that, for the years 2022 and 2023, only investigations that had been officially closed were considered in the analysis (**Fig. 2.2**). Moreover, investigation reports frequently lack clear attribution of causes or fail to specify whether weather-related factors played a role. Additionally, the observed decrease in the number of recorded occurrences during the period from 2020 to 2022 – particularly in 2020 and 2021 – can be attributed to the operational impacts of the global COVID-19 pandemic, which led to a significant reduction in railway activity [2].

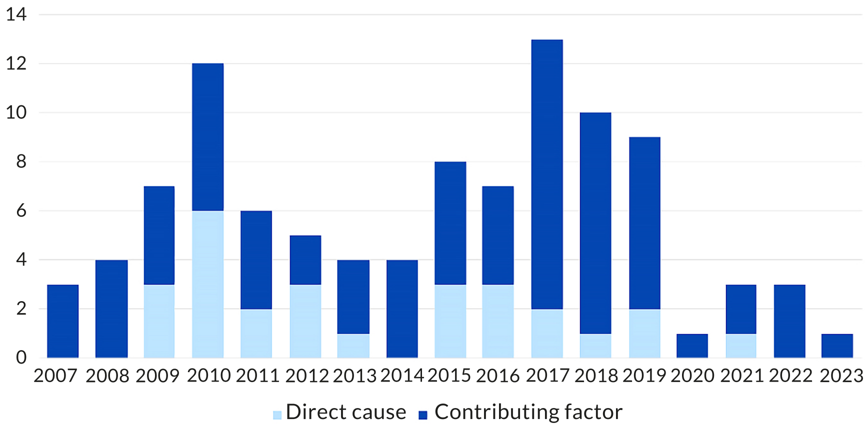

Fig. 2.2 Dynamics of weather-related significant accidents on railway
Source: [2]

National safety authorities shall also report the economic impact of significant accidents.

The EU Directive on Railway Safety [7] set up the following total and relative (to train-kilometers) indicators of economic impact of accidents: number of deaths and serious injuries multiplied by the value of preventing a casualty (VPC), cost of damages to environment, cost of material damages to rolling stock or infrastructure, cost of delays as a consequence of accidents.

When assessing its own costs related to incidents, a railway company cannot rely entirely on the Railway Safety Directive, as the calculation methodology presented there covers both internal and external costs (born by other stakeholders, not the railway company itself) and does not provide a comprehensive list of cost categories.

2.2.1 Costs of people's injury and fatality

Railway staff, passengers or unauthorized users can be affected during railway accidents. Among stakeholders, who take these costs, are transport companies, transport services users (passengers, companies), employers.

Costs of people's injury and fatality include [8, 9]:

– medical costs;

– production losses costs: the loss of production or productive capacities;

– human costs: immaterial cost of lost quality of life and lost life years;

– administrative costs: police, fire service, insurance, legal costs, personal property.

This classification was used in [8] to calculate transport externalities related to accidents and should be analyzed and adopted to be applicable to calculate companies' internal costs of climate related incidents.

Human costs are calculated as a percentage of value of statistical life (VOSL) [8].

The VOSL is the amount of money that a community of people are willing to pay to lower the risk of an anonymous instantaneous premature death within that community. It can be calculated by dividing the amount people are willing to pay by the change in mortality risk. VOLS is defined based on willingness to pay (WTP) studies.

Medical, administrative costs and costs of property damage are calculated based on the actual costs. Based on data gathered from 31 European and non-European countries the values of the costs for using on the macrolevel were estimated [8]. The average values are presented in **Table 2.2**.

The methodology for calculating productivity (or production) losses is described in **Section 2.5**, as the same approach can be applied to estimate both productivity losses due to injury and those resulting from extreme heat exposure.

Table 2.2 External accident cost component per casualty for the EU28, EUR2016

Accident type	Human costs	Production loss	Medical costs	Administrative	Total external cost per casualty
Fatalities	2 907 921	361 358	2 722	1 909	3 273 909
Serious injuries	464 844	24 055	8 380	1 312	498 591
Slight injuries	35 757	1 472	721	564	38 514

Source: [8]

Costs of injury and fatality taken by the company can by direct and indirect.

Direct costs include medical expenses, compensation, disability payments, legal fees, regulatory fines and penalties.

Indirect costs include loss of productivity, operational disruptions, increased insurance premiums, loss of trust from employees, hiring costs, training costs, financial repercussions from reputational damage.

2.2.2 Costs of train delays

In the EU Directive on Railway Safety [7], the costs of delays because of accidents means the monetary value of delays incurred by users of rail transport (passengers and freight customers) because of accidents, calculated by the model of monetary value of travel time savings.

The *monetary value of passenger train travel time savings* represents the amount of money a person is willing to pay to reduce their travel time and is calculated as a percentage of the traveler's hourly wage or income. Different travel purposes (personal, business) and types of travel (local, intercity) may have different values.

The *monetary value of freight train travel time savings* represents the monetary worth of reducing travel time for freight shipments and is usually expressed in money units per hour.

Such an approach is applicable in the context of planning new infrastructure and supporting decision-making primarily at the macro level, as the value of time savings serves as an indicator that incorporates both internal and external costs. Within the framework of the proposed concept for evaluating the internal climate-related costs of a railway company, it is essential to determine the actual costs incurred.

The total trains delay cost is calculated based on the cost per train-hour, the number of trains delayed, and the length of the delay [8]

$$CD_A = CM_P \cdot DT_P + CM_F \cdot DT_F, \tag{2.1}$$

where CM_P – cost of 1 minute of delay of a passenger train; DT_P – total time of all passenger trains delay, minutes; CM_F – cost of 1 minute of delay of a freight train; DT_F – total time of all freight trains delay, minutes.

Train delay costs include:

1. *Cars delay costs* refer to the cost of railroad-owned cars that are delayed and therefore are unavailable for use elsewhere. Privately owned cars shouldn't be

considered, excluded from this analysis because they are not directly paid by the railway company, and considered as external costs.

2. *Locomotive delay costs* are estimated based on the locomotive depreciation that occurs due to the delayed locomotives not being available for use elsewhere.

3. *Extra fuel and electricity costs* are the costs related to extra fuel consumed due to the delay.

4. *Crew labor costs*. Train crews (drivers, conductors, onboard staff) typically work scheduled shifts with strict limits defined by: labor laws, Union agreements, safety regulations. If a train is delayed and a crew's working hours exceed their scheduled duty, the employer must pay overtime rates, possibly provide relief staff or accommodation/transport.

5. *Passenger compensation* under delay refund policies and *penalties* paid to other operators in shared tracks and contractual penalties for delayed cargo [9].

2.2.3 Damage costs

Cost of damage to environment means costs that are to be met by railways, in order to restore the damaged area to its state before the railway accident.

Cost of material damage to rolling stock or infrastructure means the cost of providing new or repair rolling stock or infrastructure, with the same functionalities and technical parameters as that damaged beyond repair, including also costs related to the leasing of rolling stock, as a consequence of non-availability due to damaged vehicles [7].

Both types of costs are calculated as actual costs.

2.2.4 Incidents investigation costs

The objective of accidents investigation is to improve, where possible, railway safety and the prevention of accidents.

As it was mentioned before, NIBs obligatory investigate and report serious incidents. The decision to initiate investigations into other types of incidents is guided by necessity. Considering established evidence indicating a rise in climate-related incidents, such investigations are deemed essential for informing effective preventive measures.

To effectively investigate climate-related accidents in the rail industry, additional tools beyond traditional accident investigations should be applied. These include advanced modeling, predictive analytics, and data-driven risk analysis using techniques like Bayesian networks and machine learning. Integrating historical data with weather forecasting and utilizing knowledge graphs can help identify risk propagation patterns and inform targeted risk mitigation strategies.

By leveraging these tools, railway operators can gain a deeper understanding of climate-related risks, improve accident investigations, and implement more effective mitigation strategies to ensure the safety and reliability of their systems. Attracting additional investigating methods and tools requires additional costs.

Analyzing the report of serious climate related accident of derailment of a passenger train at Carmont (Aberdeenshire, UK) on August 12, 2020 [10] the incident investigation methods and tools related to the climate impact were identified (**Table 2.3**).

Table 2.3 Investigation methods of climate related serious incident

Name of investigation method	Description of the investigation method
1	2
Not climate related	
On-site inspection	Physical investigation of the accident scene including debris, track damage, and infrastructure condition
Evidence collection	Gathering of CCTV footage, train data recorders, infrastructure records, and witness interviews
Parallel investigations (with ORR/Police)	Legal and regulatory reviews conducted alongside RAIB's technical investigation
Audit and assurance review	Examining project and inspection records, including failures to audit or report design deviations
Train crashworthiness analysis	Technical assessment of how the train design affected derailment outcome and occupant safety
Climate related	
Weather and rainfall analysis	Use of Met Office radar and rainfall modelling to determine the intensity and return period of rainfall leading up to the event
Drainage design and construction review	Assessment of how the drainage system was designed vs. how it was constructed; including structural flaws and bund formation
Infrastructure modelling (AECOM)	Engineering simulations to test how the drainage system would perform under the rainfall conditions
Risk management evaluation	Evaluating network rail's response procedures for extreme weather and how risks were assessed and mitigated
Historical precedent comparison	Comparing findings with past landslips and derailments involving weather or drainage failures
Geotechnical risk monitoring review	Investigating how real-time monitoring tools (e.g., NRWS) were used or neglected during weather events

Continuation of Table 2.3

1	2
Emergency operations assessment	Reviewing operational decisions, route control responses, and failure to reduce speed after extreme rainfall
Partially climate related	
Root cause analysis	Identifying immediate, causal, and underlying factors contributing to the derailment
Safety recommendation development	Issuing formal recommendations to improve safety procedures, design, maintenance, and response

Source: authors' development based on [10]

Short description of the accident: the immediate cause of the derailment was the train striking debris that had been washed out from a steeply sloping drainage trench onto the track following exceptionally heavy rainfall. This rainfall – measured at 51.5 mm in just over 3 hours – was considered a 100- to 144-year return period event, categorized as an extreme climatic event. The drainage system failed to handle the volume and concentration of surface water due to construction defects and deviations from the original design, resulting in a washout and obstruction of the track.

The calculation of additional costs for climate impact-related investigation methods and tools should reflect actual incurred expenditures.

Extreme weather events increasingly affect the integrity and functionality of railway infrastructure, leading to the need for unplanned maintenance and repair activities. These interventions, in turn, result in higher operational and maintenance expenditures for railway companies.

2.3 Maintenance costs

In the context of long-term adaptation strategies, it may become necessary to redesign specific infrastructure components and technical systems to enhance their resilience to extreme climatic conditions. Such engineering and design decisions require substantial financial investment and must be supported by a thorough economic justification.

A widely recognized tool for guiding these investment decisions is *life cycle cost (LCC) analysis*, which offers a comprehensive framework for evaluating the total cost of ownership of an asset over its entire service life. This methodology encompasses all cost components associated with the design, production, installation, operation, maintenance, and eventual disposal or decommissioning of infrastructure assets. *LCC* analysis allows decision-makers to compare alternative adaptation solutions not only in terms of their initial capital costs but also in relation to their long-term economic efficiency and performance under changing climatic conditions. Formula for *LCC* calculation [11]

$$LCC = C_A + C_{OS} + C_{OP}, \tag{2.2}$$

where C_A – acquisition costs: include the costs of design, fabrication, production, manufacture, installation, and other costs related to the development stage; C_{OS} – operation and support costs: include the cost of operations, maintenance (inspections, repairs, and replacements), support, and failure costs during the operational life of the asset; C_{OP} – phase-out costs: net salvage value, which includes residual or salvage value, dismantling cost, and disposal cost.

To evaluate initial climate related maintenance costs the operation and support costs of the *LCC* formula should be considered. The research of switches and crossings maintenance in the extreme weather conditions conducted in Sweden [12] concluded that the frequency of climate related maintenance cases increased.

Table 2.4 presents an overview of maintenance actions performed on switches and crossings (S&C) in Sweden due to climatic failures. The table categorizes these actions by frequency and associated cost shares under both climatic and non-climatic operational modes. The most frequent intervention is snow cleaning (41.88%), accounting for the majority of climatic-related maintenance costs (66%). Other common actions include general cleaning, adjustment, and washing. Less frequent yet significant tasks – such as lubrication, control, repair, and recovery – are also listed, each with cost implications varying between climatic and non-climatic conditions. The table highlights the dominant role of winter-related maintenance in overall S&C upkeep under Sweden's climatic conditions [12].

Maintenance and repair costs reflect the actual expenditures incurred by the railway company as a result of extreme weather impacts. These costs are calculated using a discount rate to account for the time value of money in long-term financial planning [12]

$$LCC = \sum_k \sum_i \sum_j = \frac{1}{(1+r)^k} \frac{1}{MTBF_{ij}(k)} \left\{ C_{P_{ij}} + MTTR_{ij} \left(n_{L_{ij}} C_L + C_{E_{jl}} \right) \right\}, \tag{2.3}$$

where *i* – action type; *k* – year's duration; *j* – component type; $MTBF_{ij}(k)$ – mean-time-between-failure of component *j* and a failure mode associated with action *i* for year k^{th}; $MTTR_{ij}$ – mean-time-to-repair of component *j* (in minute units) and a failure mode associated with action *i*; n_L – number of workers needed to give the action; C_L – labor cost (in monetary units/hour); C_E – equipment cost needed to carry out the intervention.

Table 2.4 Maintenance action with switches and crossings because of climatic failures in Sweden

Action	Frequency, %	% of costs for climatic mode	% of costs for non-climatic mode	Description
Show cleaning	41.88	66	0	Removal of snow and ice during the winter season
Cleaning	26.20	15	4	Remove debris, sand, stones, and other foreign objects
Adjustment	9.6	4	25	Correction of the geometric features or positional misalignment of S&C after standard measurement
Washing	9.47	11	5	Cleaning of turnout components using a fluid or other relevant medium
Lubrication	4.12	1	10	Applying a substance such as oil or grease to S&C components to minimize friction and allow smooth movement
Control	1.84	1	18	Gauging and functional check of the state of the system
Repair	1.33	1	30	Maintenance actions are carried out to return S&C to a state where it can perform the desired function by replacing components, welding, and grinding
Recovery/restoration	1.05	1	9	Resetting and returning the S&C component to initial or calibrated status after failure; performing regular standard operational procedures
Others	4.06	–	–	All other actions, e.g., grinding, tamping, tightening, and etc.

Source: [12]

2.4 Costs associated with shifts in passenger behavior driven by climate change

Modal shift to railway refers to the change in transportation choices where people and goods move from modes like cars, airplanes and trucks to trains. This shift can be influenced by various factors, including environmental concerns, infrastructure improvements, and policies.

Rail transport is often seen as more sustainable and environmentally friendly due to lower CO_2 emissions and greater energy efficiency. 0.5% of greenhouse gas emissions produced by transport refer to railways [1].

In spite on the boosting modal shift at all levels the results still haven't reached the expected level (**Fig. 2.3**). The 7% to 5.1% decline in passenger transport in EU was primarily caused by the COVID-19 pandemic, during which railway travel bans were implemented and public confidence in rail transport significantly declined. The railways have still not fully recovered from the pandemic period. Although the share of passenger transport by rail returned to 8% in 2023, the planned dynamics of modal shift have slowed down. Freight transport experienced a more stable trajectory, as it was not as significantly impacted by the pandemic as passenger transport.

Railways benefit from the modal shift, as a substantial amount of investment has been directed toward the development of railway infrastructure, and additional income is expected from the increase in passenger traffic. This can be considered as an indirect positive impact on railways from climate change. EU supports 55 projects for railway infrastructure on the core Trans-European Transport Network (TNT) on 1.6 billion EUR including Rail Baltica and railway line between Lyon and Turin [13].

It is also expected from railway to co-fund the infrastructure transformation to speed up the modal shift.

The survey shows that for the most regions price, safety, convenience, reliability and speed are the main factors for passengers when choosing their mode of transport (**Fig. 2.4**). Sustainability-related aspects seem to play only a minor role for passengers in their travel selection. The results of the research of sustainability behavior, 87% of customers expressed an interest in sustainable products, but only 12% would be willing to pay a premium for such sustainable products or services. So, modal shift can be driven by promotion of sustainability of railways among civil society and improving quality of rail travels.

Communication with a mass audience is a key component in creating awareness of rail services and fostering the desire to travel again, and rail operators worldwide raced to create vivid and compelling marketing campaigns to do so for after pandemic recovery. This experience is a strong background for further promotion of railway transportation in order to achieve modal shift targets [15].

It's also expected that rail travel demand can change. For example, some share of passenger can prefer rail to air travel as more safe and reliable transport mode in the condition of extreme weather for medium distance trips; some passengers probably will avoid travels at all then the weather conditions are risky; new global trend as teleworking will reduce travels on work purpose at all or if the weather conditions are not preferable.

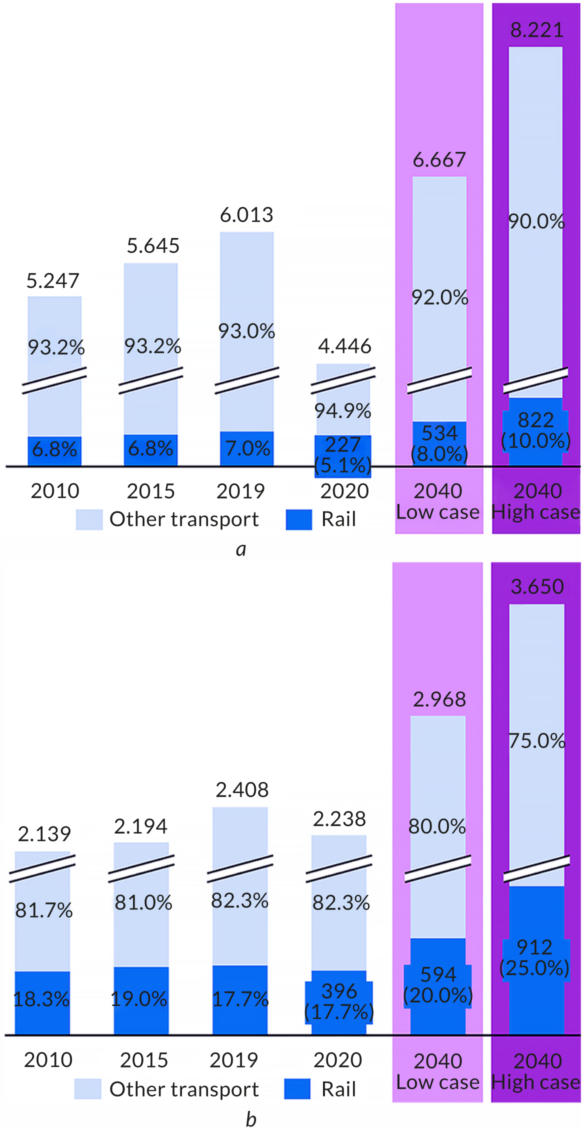

Fig. 2.3 European transport trends:
a – passenger transport, millions pkm; *b* – freight transport, millions tkm
Source: [14]

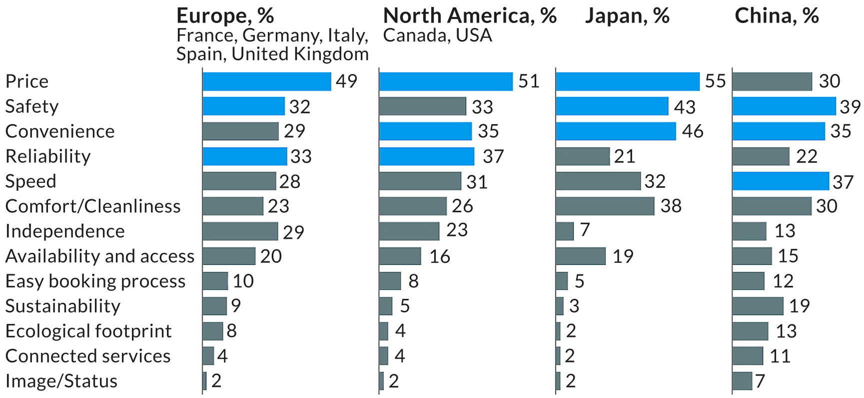

Fig. 2.4 Drivers for passengers when choosing their mode of transport
Source: [16]

In USA 10% of people will work remotely till 2025. Expected decrees in the number of business trips per person is 21% in China, 24% in USA and Europe [16].

Influence of such kind of factors can be evaluated by monitoring the dynamics of trips during different weather conditions, conducting surveys among customers.

A key challenge is to identify and quantify the extent to which cost increases are driven by climate-related causes. Furthermore, the impact of climate change on passenger behavior remains insufficiently studied and represents an ongoing subject of academic inquiry.

2.5 Costs associated with reduced worker productivity caused by extreme temperatures

Railway operational staff frequently work under conditions of extreme heat. Sustained exposure to elevated temperatures can result in a variety of physical and cognitive challenges, including heat stress, dehydration, fatigue, and diminished decision-making capacity. These impacts compromise worker health and safety, elevate the likelihood of human error and equipment malfunction, and contribute to productivity losses.

Certain railway occupations and tasks have been identified as particularly susceptible to high temperatures (**Table 2.5**). *Vulnerability* in this context refers to the extent to which individuals are likely to experience adverse effects from heat exposure. It is typically understood as a combination of two key factors: *exposure* and *sensitivity.*

Exposure denotes the intensity and duration of time workers spend in high-temperature environments. This can be influenced by factors such as geographic location and climate (e.g. seasonal heat patterns, humidity, urban heat islands), environmental settings (sun vs. shade, indoor vs. outdoor workspaces, airflow, and heat-retaining surfaces), as well as the duration, frequency, and scheduling of tasks. Infrastructure characteristics also play a role in determining exposure levels.

Sensitivity relates to how vulnerable a worker is to the effects of heat once exposed. This can vary based on individual attributes (e.g. age, health status, level of acclimatization, hydration, and nutrition), job demands (e.g. physical intensity, mental workload, task importance, stationary vs. mobile work), and the characteristics of the working environment [4].

Understanding which roles within the railway sector are most affected by high temperatures is essential for developing targeted mitigation and adaptation strategies.

Table 2.5 The impact of high temperatures on railway workers' productivity

Occupation	Tasks description	Level of exposure	Level of sensitivity
Maintenance workers	Manual labor such as repairing and maintaining tracks, signaling systems and electrical equipment	High	High
Track inspectors, shunting staff and engineers	Inspection and maintenance of railway tracks and infrastructure, and assessing the condition of critical components such as bridges and tunnels	High	Moderate to high
Train operators	Driving and navigating trains, monitoring signals and responding to operational changes	Moderate to low	High
Signal and control room operators	monitoring and controlling train movements, ensuring the safe operation of railway systems and responding to emergencies	Low to moderate	High
Station and platform staff	Include managing passenger flow, assisting passengers, overseeing ticketing and handling emergencies	High	Moderate to high
Electrical and signaling technicians	Maintaining and repairing electrical and signaling systems and responding to technical failures	High	High
Security and emergency response teams	Ensuring passenger safety, managing emergencies and responding to medical incidents or security threats	Moderate to high	High
Cleaning and support staff	Cleaning stations, platforms and trains and performing maintenance tasks in high-traffic areas	Moderate to high	Moderate

Source: [4]

The estimation of heat effect can be performed by the costs of productivity loss related to paid work, which is calculated by multiplying the relevant number of work days lost with a wage rate estimate [17].

Two types of productivity losses are identified related to paid work: absenteeism and presenteeism [18].

Absenteeism refers to productivity losses related to not attending work due to ill health. Such losses occur if people are too sick to attend work, or if people need to visit medical professionals during working hours.

Presenteeism relates to reduced productivity at work due to health problems. If a person suffers from ill-health but does attend work, he or she may not be able to function equally well in terms of quality and/or quantity compared with when he or she was in full health. The costs associated with presenteeism can be significant and can be influenced by such factors as the social security system in a country. If employees do not get paid during sick leave, they may be more inclined to attend work while being ill. Costs associated with presenteeism seldom included in economic evaluations. Productivity cost estimates based on absenteeism alone will poorly reflect full productivity costs.

Two more aspects should be considered while estimating costs of productivity losses. These are multipliers and compensation [18].

Multipliers is a phenomenon in which the ill-health of an individual employee not only reduces their own productivity but also negatively impacts the productivity of colleagues – particularly in work environments with high team interdependence and limited flexibility for substituting or reallocating tasks among staff.

Compensation is the process by which lost productivity due to an employee's ill-health is offset – either by colleagues assuming additional workload or by the ill individual making up for the lost output upon returning to work. This compensation can occur during normal working hours or through extra work time, and while it may reduce the net societal cost of productivity loss, it can also impose additional strain on the workforce.

2.6 Costs of reputational loss

Disruption of transport operations and infrastructure by extreme weather damage can lead to both revenue and reputation losses for rail operations.

Reputational damage is often difficult to measure directly, but its effects on a company can be substantial. Research shows that shifts in a company's reputation can significantly influence its market value. Since a firm's stock price is essentially based on the present value of its expected future earnings, any incident that harms its reputation – and thereby reduces anticipated cash flows can lead to a decline in share value [19].

Reputational risk can lead to various forms of financial loss, including:

– loss of existing or potential customers, which not only reduces expected revenues but may also increase costs associated with damage control;

– departure of key employees or executives, rising recruitment expenses, or productivity losses due to staff disruptions;

– reduction in the number or quality of current and future business partners;

– higher costs of obtaining financial capital or credit;

– increased expenses resulting from stricter government regulations, fines, or other legal penalties.

To estimate reputation losses of the railway because climate event study methodology can be applied [20]. Here the reputational losses are defined as any financial losses that go beyond the officially disclosed or expected loss. This approach assesses how specific even to (favorable or unfavorable) affects a company's reputation by examining its market reaction to events that have already taken place. To carry out this type of analysis, it is essential to isolate the reputational factors that drive company performance from other influencing variables.

An event study (**Fig. 2.5**) typically involves three key phases [20]:

– the *estimation window*, which serves as the baseline period to establish normal performance;

– the *event window*, during which the actual event occurs and its immediate impact is measured;

– the *post-event window*, which tracks any lasting effects following the event.

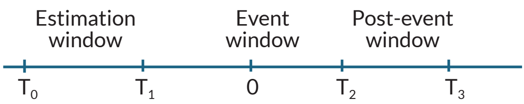

Fig. 2.5 Timeline of event study
Source: [20]

An event is defined as a point in time in which a company makes an announcement, or a significant market event occurs, in that case of a reputational type.

From a quantitative perspective, one established method evaluates the relationship between reputational loss and a company's market value decline. In this approach, reputational loss is defined in economic terms: if the decrease in market value exceeds the amount of the announced operational loss, the difference is attributed to reputational damage. The method takes into account factors such as the size and nature of the loss, as well as the company's corporate governance structure, using the stock market's response to the public announcement of the loss as an indicator of reputational impact [19].

2.7 Conclusions

Although many of the cost categories examined in this Chapter – such as incident-related costs and maintenance expenditures – have long existed in the operational framework of railway companies, climate change introduces a new dimension to their evaluation. It is essential to distinguish which portions of these costs can be directly attributed to climate-related impacts. Such differentiation enables a more accurate assessment of how climate change affects the overall economic performance of a railway company.

A critical task in this process is the detailed analysis of costs within each identified category to prevent double counting. Without this precision, estimates may become inflated or misleading, undermining the reliability of economic evaluations and risk assessments.

Another priority is the establishment of a comprehensive, structured database of baseline and climate-related cost data. This would serve as a foundation for consistent and repeatable calculations, thereby supporting informed decision-making on climate adaptation strategies.

Additionally, the methods for estimating costs associated with changes in passenger behavior due to climate change remain insufficiently studied. Given the potential implications of modal shifts, altered travel preferences, and reduced demand in extreme weather conditions, further research in this area is both timely and necessary.

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CHAPTER 3

Ecological state of modern soil cover in agrocenoses of the Greater Caucasus Sheki region

Roza Mammadova
Turkan Hasanova
Matanat Aliyeva

Abstract

The article presents climate data, soil moisture, humus content, nitrogen and other key microbiological indicators of the territory (2023–2024). Agricultural production has made great strides in the last two decades and occupies a leading position not only in the Sheki region, but also in the country. Deforestation to meet the growing needs of the population for firewood is a very sad situation. Forestation work in the Sheki region, considered the most beautiful tourist center of Azerbaijan, is one of the most important issues posed by the state to environmentalists. The article presents the results of forest restoration work carried out on the experimental site of the Sheki Regional Research Center, as well as studies carried out on soils spread under trees that are already 80 years old. Soil surveys conducted using modern methods are considered an innovation for Azerbaijan. The results obtained can be used in subsequent studies coordinates are 41°15'45.0"N 47°12'57.6"E; 41°15'54.8"N 47°13'12.5"E; 41°16'03.8"N 47°13'14.2"E; 41°16'03.3"N 47°13'34.9"E; 41°16'29.6"N 47°12'52.0"E. The study of microbial mass is very important for the ecological assessment of the studied soils. The maximum number of actinomycetes was found in the virgin gray forest soil on the hillock, where it amounted to 360 thousand CFU/g, which is 5 times more than in the same soil horizon of the depression on the natural soil and 30 times more than in the soils of both elements of the microrelief on the fallow land. In taxonomic terms, micromycetes in the studied gray forest soil are represented by the following dominant species: *Penicillium notatum*, *Penicillium chrisogenum*, *Trichoderma viride*, *Trichoderma lignorum*, *Aspergillus niger*, *Mucor* ssp., *Paecilomyces* ssp., *Crustosum* ssp. Representatives of the genera *Fusarium* and *Monatospora* are rare. As a result of the analysis of the obtained data, the total reserves of organic matter of the secondary spruce forest were determined, which amount to from 21.5 to 32.7 kg·m^{-2}.

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Keywords
Forest resources, vegetation, reforestation, correlation, regression analysis, soil-microbiological characteristics, organic matter.

3.1 Introduction

To assess the sustainability of agrocenoses, it is advisable to use a set of criteria and indicators that allow quantitative interpretation of its variability under the influence of agrogenic factors. Microbiological and biochemical indicators reflect the dynamic properties of soils and serve as indicators of life processes in the soil [1, 2]. Currently, the issue of efficient land management and rational use of forest resources is acute. The world community is increasingly aware of the need to preserve and restore forests. One of the most important production tasks of forestry in the area of forest reproduction is the cultivation of high-quality planting material of trees and shrubs. The quality of planting material and its hereditary properties largely determine the productivity and sustainability of future plantings [3, 4]. The issue of efficient land management and rational use of forest resources is acute. The world community is increasingly aware of the need to preserve and restore forests [5].

The development of livestock industries entails an increase in the need for feed grain, coarse and succulent feed, therefore, it will be necessary to expand existing agricultural lands at the expense of lands that were not previously cultivated or were long ago transferred to a fallow state. As for planting material for reforestation, there is currently a shortage of high-quality raw materials (seedlings) in the Azerbaijan, existing nurseries use old methods used since Soviet times for growing.

Successful reforestation (afforestation) requires a significant number of seedlings and saplings grown in forest nurseries. Effective implementation of reforestation measures is possible only on a soil-typological basis, in connection with which the consideration of soil and ground factors comes first [6]. This becomes especially relevant when growing planting material in forest nurseries, under conditions of intensive agricultural technology, which makes nursery farms similar to agricultural production [7]. Currently, the main ways of intensifying work in the agricultural sector are in the area of implementing precision farming systems (**Fig. 3.1**).

Similar approaches can be fairly transferred to the organization of work in forest nurseries. Precision farming is based on digital field maps compiled using geographic information systems. This allows systematizing the available information on the state of the soil, as well as updating it, receiving visual data in the form of various maps and cartograms, automating the accounting of all economic activities on the territory of the nursery, and providing information support for decision-making [8, 9].

Fig. 3.1 Cartogram of the current state of the fields in the Sheki Regional Center: *a* – soil plan of part; *b* – soil pH; *c* – acidity level of soils

3.2 Methods

The research was conducted on the territory of the Sheki Regional Center of the educational and experimental forestry enterprise in Sheki. The forest nursery with an area of 33 hectares is located on the territory of the Sheki-Zagatala economic district in the 11^{th} quarter of the district forestry. The nursery provides planting material for forestry production in Sheki and other farms in Sheki-Zagatala economic district; the assortment is dominated by coniferous species, most often used in reforestation. The work program included a soil-agrochemical survey of the nursery fields using GIS technologies (laying and morphological description of sections, sampling to determine the physical, physicochemical and chemical properties of the soil), conducting a topographic survey of the nursery territory, determining the degree of weed infestation of the nursery fields. All collected information was digitized and combined into a single geographic information system. Georeferencing of soil survey points, relief topographic survey points, and nursery fields was carried out using GPS/GLONASS navigation and the NextGIS mobile application. In the soil laboratory of the Institute of Soil Science and Agrochemistry, the main physical (density, solid phase density, moisture), chemical and physicochemical properties of soils (actual, exchangeable, hydrological acidity, the sum of exchangeable bases, cation absorption capacity, base saturation, content of available forms of nitrogen, phosphorus and potassium, humus content) were determined for the selected soil samples. The QGIS system was chosen as the software for creating the nursery GIS. QGIS is a free, cross-platform, open-source system. It supports a wide range of vector and raster formats, has a convenient Russified interface and a large number of accessible methodological materials. In addition, QGIS is directly linked to the NextGIS Mobil mobile application, as these are related developments. The SAS program was used to obtain a georeferenced topographic base [10–13].

3.2.1 Physicochemical properties

The work uses generally accepted methods for studying the physical, chemical and physicochemical properties of soils. Phytotoxicity of soils was carried out according to the method of N. Krasilnikov in an aqueous extract obtained from humus and buried horizons of the studied soils when comparing them with the control (distilled water). Identification of microscopic fungi was carried out according to the Identifier of M. Litvinov, actinomycetes – according to the Identifier of G. Gause et al., eubacteria – according to the Identifier of Bergey's bacteria. The methodological approach for conducting laboratory analyses of the biochemical activity of soils was the express method of T. Aristovskaya, M. Chugunova, the essence of which is that the rate (in hours) of decomposition of a nitrogen-containing organic compound (urea) and changes in the pH of the air by 1.5–2.0 units due to the release of ammonia are recorded. Agrophysical properties are considered to be among the most important elements of soil fertility. The main physical properties include bulk density and solid phase, porosity, structural-aggregate composition and water resistance of structural units [14, 15].

3.3 Results

3.3.1 Microbiocenoses

The studies were conducted in a long-term stationary experiment, established in 2023–2024 on gray forest medium loamy soil in the southern region of the Greater Caucasus. A fairly high humus content is observed in the organogenic horizons. Its amount decreases rapidly with depth, especially noticeable in the soils of the pits located on elevated elements of the microrelief. Thus, at a depth of 30–50 cm of pit 1 on the deposit, there is less than 2% humus, and in the upper horizon of pit 3 on natural soil – a little more than 2.5%, which is due to the greater mineralization of humus here compared to depressions, caused by higher soil heating. In depressions, both on virgin soil and on deposits, the amount of humus decreases slowly down the profile and even at a depth of 50–70 cm remains quite high, amounting to more than 3%. The upper horizon of section 4 is significantly enriched with humus, which is 3 times more than the similar horizon of section 3. Fallow and virgin gray forest soils have significant differences in the content of actinomycetes. In fallow soils, their number is 10–11 thousand CFU/g on the micro-elevation and significantly lower in the subsurface and buried horizon of the micro-depression (2.5–1.6 thousand CFU/g). Consequently, the processes of organic mineralization due to actinomycetes in fallows occur less deeply and less intensively, as also evidenced by the large range of C:N. However, in virgin gray forest soil, especially on the elevation, the number of actinomycetes is maximum (300 thousand CFU/g), which is consistent with the smaller range of C:N and the low content of organic matter in the horizon, A (10–20), due to its active mineralization by actinomycetes. In taxonomic terms, the dominant actinomycetes that we were able to identify to the species level belong to the *Albus* section of the *Albus* series, *Streptomyces*/*Albus* species, and to the *Cinereus* section, *Achromogenes* series, *Streptomyces sporocinereus* species. The quantitative index of denitrifiers taken into account on the Giltai medium is very low (0.1). They were found only in the depressions of the deposit and natural soil.

Consequently, the processes of nitrate reduction, the amount of which is apparently insufficient due to the shallow degree of mineralization of organic matter in the deposit, are greatly slowed down [14]. In all horizons of the studied gray forest soils of the fallow and natural lands, a large number of oligonitrophilic and nitrogen-fixing eubacteria are present on both elements of the microrelief, counted by the standard method on the Ashby medium. The number of oligonitrophils on the fallow land is from 9.0 million CFU/g to 12 million CFU/g in the soil of the upland and

15 million CFU/g in the depression. On the natural soils, their number is even higher: 50 million CFU/g on the hillock and 60 million CFU/g in the depression.

The high number of oligonitrophils in the microbiocenoses of the studied samples of gray forest soil compared to other ecotrophic groups of microorganisms can be explained by small reserves of nitrogen, the amount of which is "compensated" by both the process of nitrogen fixation, enriching the soil with nitrogen, and the activity of dissipotrophs assimilating low concentrations of nitrogen present in the soil in a "dispersed" state [15]. In taxonomic terms, free-living oligonitrophils – dissipotrophs in the gray forest soil of the region are represented mainly by pseudomonads and bacilli, and diazotrophs are rare and are represented by Azotobacter.

3.3.2 Vegetation

It should be noted that the humus content in the deposit is 1.5 times less than in natural soils, which is associated with the activation of soil dehumification processes during development. However, the differences in humus content between soils of different positions along the microrelief are insignificant and amount to less than 1% in the upper horizons. Due to surface leveling and mechanical mixing of the soil, many indicators, including humus content, have become closer in their values [16, 17]. During the field stage of the research, it was established that the nursery soils are classified as arable gray medium or light loamy. A satellite image from the operator DigitalGlobe was used as the basis for the placement of all spatial objects [18]. Shapefile format was chosen as the format for presenting GIS data. The soil plan was directly constructed using the interpolation method depending on the genesis and morphology of the soils, the granulometric composition and the terrain [19–21]. When determining the degree of weed infestation in the fields, it was found that perennial weeds have the greatest species diversity, the most common weeds being *Taraxacum officinale*, *Phleum pratense* and *Tripleurospermum inodorum*, *Stellaria media* L., *Galinsoga quadriradiata*, *Eragrostis curvula*, *Eragrostis pectinacea* (Michx.), *Eragrostis tef* (Zucc.), *Echinochloa crus-galli* (L.), *Fagopyrum tataricum* (L.), *Capsella bursa-pastoris* (L.), *Tripleurospermum inodorum* (L.), *Myosotis arvensis* (L.) *Viola tricolor* (L.), *Apera spica-venti* (L.), *Cirsium arvense* (L.), *Sonchus arvensis* (L.), *Barbarea vulgaris*, *Vicia cracca* (L.), *Potentilla anserina* (L.), *Lupinus polyphyllus* (L.), *Ranunculus repens* (L.), *Equisetum arvense* (L.), *Calamagrostis epigejos* (L.), *Tussilago farfara* (L.), *Geum urbanum* (L.), *Artemisia vulgaris* (L.), *Tanacetum vulgare* (L.), *Centaurea jacea* (L.), *Plantago major* (L.), *Deschampsia cespitosa* (L.), *Phleum pratense* (L.) and others. On natural cenoses, the pits were laid on a gentle slope of western exposure with a slope of less than 3°C, in its lower part (**Fig. 3.2**). In the course of scientific research conducted over many years, the bioecological properties of tree species, which are of great importance in various landscapes of Azerbaijan, have been widely studied.

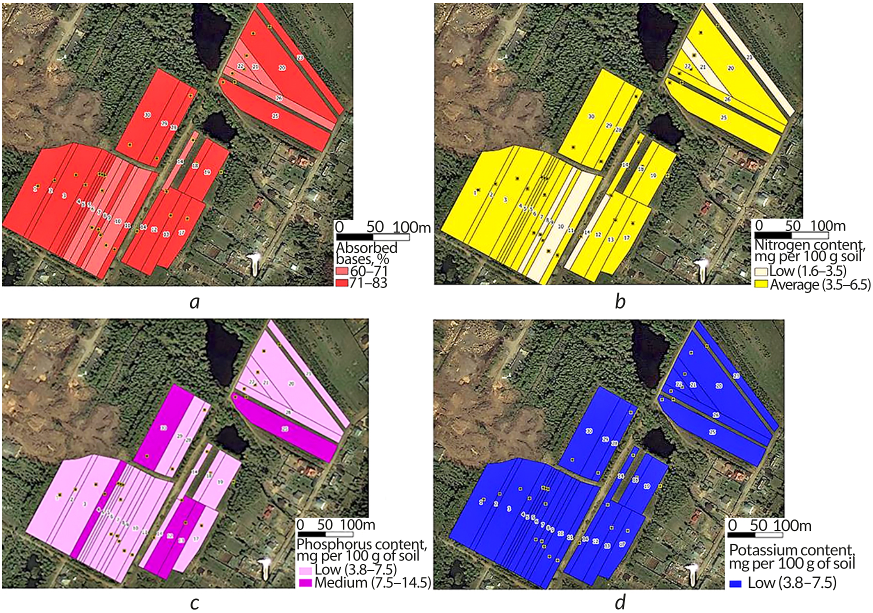

Fig. 3.2 Cartogram of some content's degree in the soils:
a – base saturation; *b* – nitrogen content; *c* – phosphorus content; *d* – potassium content
Source: by authors in 2024 year

The pits are located on a gentle slope with a western exposure with a slope of less than 4°C, in its lower part. Vegetation: mixed grass. The elevation above the depression in the forest according to the leveling traverse was 3.1 m, the diameter of the mound was 22 m. The soil on the mound effervesces from 10% HCl from a depth of 70 cm. Profile formula: O-Ad-A-AE-BE-BT-Cca, soil name: gray forest typical residual-carbonate. In the depression, the soil does not effervesce from 10% HCl throughout the profile. Profile formula: O-Ad-A-AE-A_1-A_2-A_3, soil name: gray forest with a buried humus horizon.

At the turn of the century, the period of traditional cartography was replaced by a period of geoinformation mapping and the active use of computer technologies. On the fallow land, the pits were laid on a gentle slope of southern exposure with a slope of less than 2°C (**Fig. 3.3**).

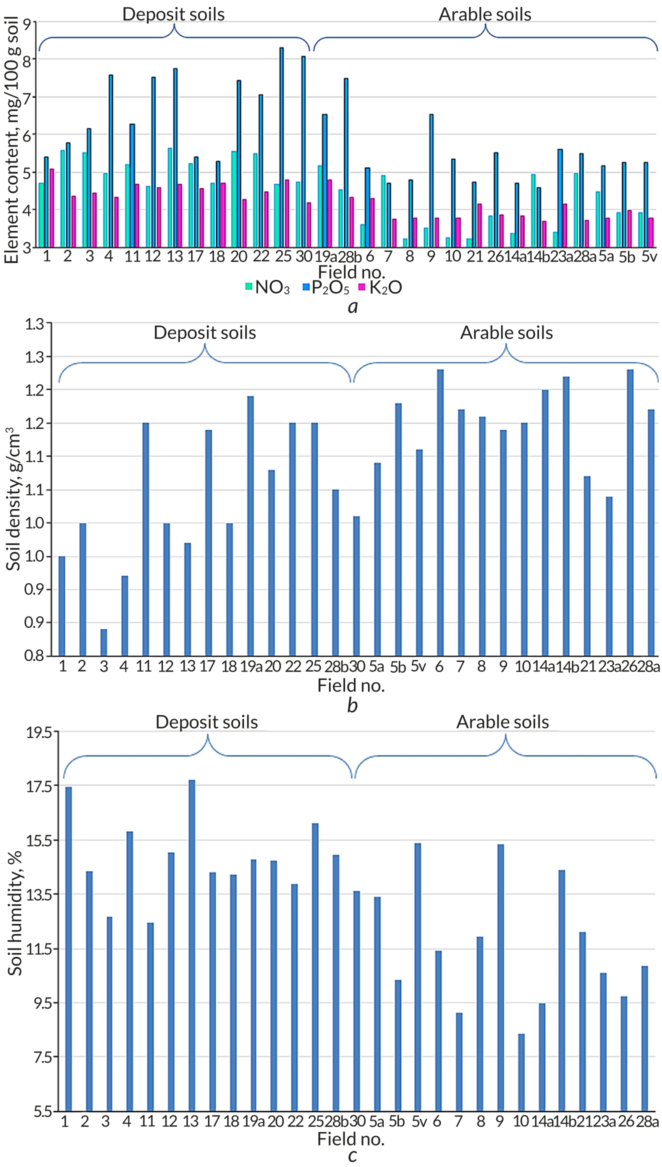

Fig. 3.3 Comparative indicators of soil parameters in the selected fields of Sheki Regional Center: *a* – element content; *b* – soil density; *c* – soil humidity

The vegetation is represented by lush forbs with birch and aspen undergrowth. The height of the micro-elevation was 40 cm, the diameter was 38 m. The soils do not effervesce from 10% HCl throughout the profile. The soil profile formula on the micro-elevation is A_1-A_1/p-AE-BE-BT-Cg, the name of the soil is gray forest gleyic. In the micro-depression, the profile formula is: A_1-A_1/p-A-AE-BE-BT-Cg, the name of the soil is gray forest with a buried humus horizon. According to the 2004 Classification, the soils on both elements of the microrelief belong to the same type – agro-gray gleyic soils of the texturally differentiated soils of the postlithogenic trunk, with the profile formula: A-AY-AEL-BEL-BT-Cg. Comparative indicators (soil density, humidity) of soil parameters in the selected fields (deposit and arable) of Sheki Regional Center were determined (**Fig. 3.3**).

The goal of analyzing the dependence of stand productivity on soil conditions based on production materials: field soil survey and forest management data. The average height of the stand (in meters) at the age of 80 years, i.e. the stand quality class, expressed in an arithmetic scale, was chosen as the indicator of stand productivity. To characterize the soil conditions, those indicators were selected from the soil survey materials that can be expressed in arithmetic scales [22], 4,549 pine stands were analyzed. Correlation analysis confirms the dependence of the stand quality (average height at 100 years) on the selected soil indicators (**Table 3.1**). Multiple R = 0.67, normalized R_2 = 0.45 with a standard error of 1.77. Of the selected soil indicators, the least significant were the capacities of the humus and podzolic horizons.

The remaining indicators have a significant impact on the productivity of pine forests and should be taken into account when forecasting forest development and forestry planning. The next stage of our analysis was to test the hypothesis about changes in the productivity of pine forests with age. The presented investigations mainly assessed the current state, dynamics, and comparative parameters of erosion, emphasizing its repercussions on fertility indicators of agricultural soils. Expanding the research was imperative to highlight the correlation between soil erosion and its consequences on the local ecosystem. Beyond the immediate impact on soil fertility, erosion can lead to enhanced sedimentation in water bodies, affecting water quality and aquatic habitats [23, 24]. Multiple linear correlation analysis confirms the dependence of the productivity of stands (average height of a stand at 80 years) on age and soil parameters (**Table 3.2**). Multiple R = 0.74, normalized R_2 = 0.54 with a standard error of 1.61. It should be noted that the coefficient of the variable "age of a stand" is significant. To confirm the independence of the sample from the age of the stands, it is possible to analyze the dependence of the age of pine forests on soil parameters (**Table 3.3**). Multiple R = 0.14, normalized R_2 = 0.02 with a standard error of 30.00.

Table 3.1 Results of multiple linear regression analysis of the dependence of planting productivity on soil properties

Variables	Regression coefficients	Standard error	*t*-statistic	*R*-value	Lower 95%	Upper 95%
Y-intersection	3.627E+01	9.889E−01	3.668E+01	3.300E−258	3.433E+01	3.821E+01
Org. hor. thickness	−9.457E−02	2.584E−02	−3.659E+00	2.556E−04	−1.452E−01	−4.390E−02
Hum. hor. thickness	1.063E−02	6.949E−02	1.530E−01	8.784E−01	−1.256E−01	1.469E−01
A_2 hor. thickness	1.477E−02	9.648E−03	1.531E+00	1.259E−0	−4.145E−03	3.368E−02
% Phys. clay	1.176E−02	4.718E−03	2.493E+00	1.270E−02	2.513E−03	2.101E−02
Moisture cont.	−1.012E−01	1.424E−02	−7.103E+00	1.411E−12	−1.291E−01	−7.325E−02
Upper gleyization layer	−1.638E−02	9.370E−04	−1.748E+01	3.039E−66	−1.821E−02	−1.454E−02
Degree of claying	−1.120E−01	7.735E−03	−1.449E+01	1.610E−46	−1.272E−01	−9.688E−02
% Phys. clay of parent rock	7.300E−03	1.794E−03	4.069E+00	4.798E−05	3.783E−03	1.082E−02

Table 3.2 Results of multiple regression analysis of the dependence of plantation productivity on age and soil properties

Variables	Regression coefficients	Standard error	*t*-statistic	*R*-value	Lower 95%	Upper 95%
1	2	3	4	5	6	7
Y-intersection	3.779E+01	9.016E−01	4.192E+01	0.000E+00	3.602E+01	3.956E+01
Soil age	−2.445E−02	7.977E−04	−3.065E+01	1.008E−187	−2.602E−02	−2.289E−02
Org. hor. thickness	−1.049E−01	2.353E−02	−4.460E+00	8.400E−06	−1.510E−01	−5.880E−02
Hum. hor. thickness	−2.406E−02	6.327E−02	−3.804E−01	7.037E−01	−1.481E−01	9.997E−02

Continuation of Table 3.2

1	2	3	4	5	6	7
A_2 hor. thickness	8.570E–03	8.785E–03	9.756E–01	3.293E–01	–8.652E–03	2.579E–02
% Phys. clay	1.405E–02	4.296E–03	3.270E+00	1.083E–03	5.626E–03	2.247E–02
Moisture cont.	–8.517E–02	1.298E–02	–6.563E+00	5.872E–11	–1.106E–01	–5.973E–02
Upper gleyization layer	–1.531E–02	8.536E–04	–1.794E+01	1.428E–69	–1.699E–02	–1.364E–02
Degree f claying	–1.119E–01	7.041E–03	–1.589E+01	2.419E–55	–1.257E–01	–9.805E–02
% Phys. clay of parent rock	5.947E–03	1.634E–03	3.640E+00	2.754E–04	2.744E–03	9.150E–03

Table 3.3 Results of multiple regression analysis of the dependence of planting age on soil properties

Variables	Regression coefficients	Standard error	*t*-statistic	*R*-value	Lower 95%	Upper 95%
Y-intersection	6.205E+01	1.675E+01	3.705E+00	2.142E–04	2.921E+01	9.488E+01
Org. hor. thickness	–4.235E–01	4.376E–01	–9.678E–01	3.332E–01	–1.282E+00	4.345E–01
Hum. hor. thickness	–1.419E+00	1.177E+00	–1.206E+00	2.281E–01	–3.726E+00	8.885E–01
A_2 hor. thickness	–2.535E–01	1,634E–01	–1.551E+00	1.209E–01	–5.738E–01	6.682E–02
% Phys. clay	9.344E–02	7.991E–02	1.169E+00	2.423E–01	–6.322E–02	2.501E–01
Moisture cont.	6.547E–01	2.412E–01	2.714E+00	6.677E–03	1.817E–01	1.128E+00
Upper gleyization layer	4.345E–02	1.587E–02	2.738E+00	6.198E–03	1.234E–02	7.456E–02
Degree of claying	7.822E–03	1.310E–01	5.971E–02	9.524E–01	–2.490E–01	2.646E–01
% Phys. clay of parent rock	–5.533E–02	3.038E–02	–1.821E+00	6.866E–02	–1.149E–01	4.235E–03

Based on production materials, the dependence of pine forest productivity on such soil properties as the thickness of organogenic horizons, the granulometric composition of the soil and parent rock, the degree of soil profile moisture, the depth of gleyed horizons and the degree of gleyization is confirmed. The change in the quality of pine forests during their growth is also statistically confirmed. All this indicates the need and possibility of developing growth standards for tree plantations taking into account soil information [25].

Modern soil cover of natural and cultivated cenoses used in agriculture of Greater Caucasus southern slope plains horizontal distribution shows the difference in relief structure of the territory (**Fig. 3.4**).

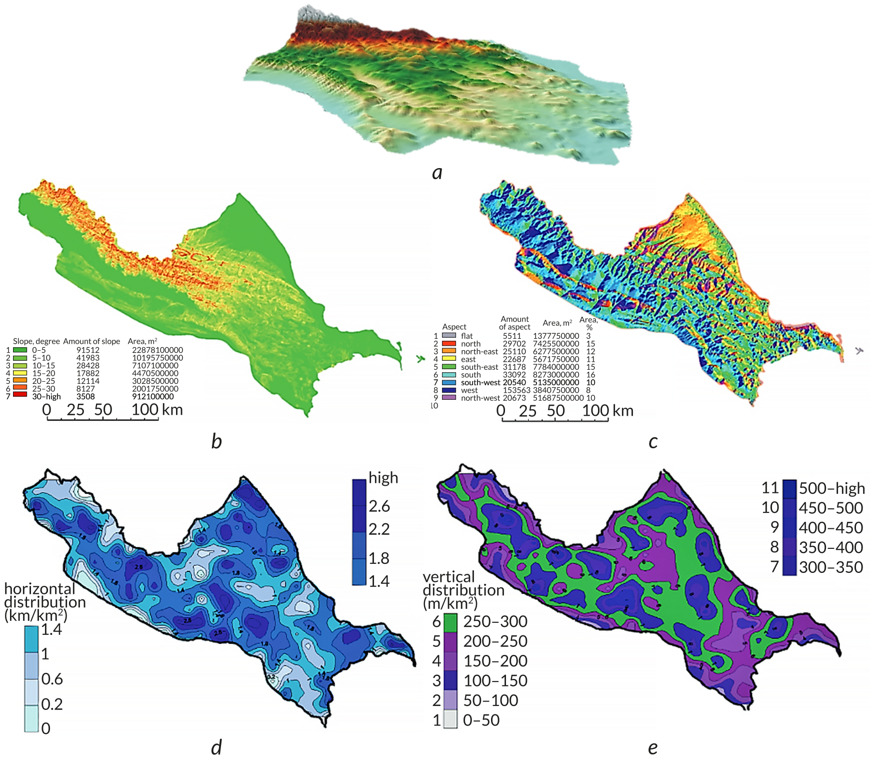

Fig. 3.4 Maps of the Greater Caucasus: *a* – map of the southeastern part of the Greater Caucasus in 3D forma; *b* – slope map of Greater Caucasus plains; *c* – aspect map of the Greater Caucasus plains; *d* – horizontal and distribution maps of the Greater Caucasus plains; *e* – vertical distribution maps of the Greater Caucasus plains

3.3.3 Discussion of the results

In developing countries, special attention is paid to the agricultural sector, which is the main condition for social sustainability. Anthropogenic impact on ecosystems creates a number of environmental problems. Unsustainable natural landscapes are destroyed under the influence of irrational management methods. There is widespread irrigation degradation, secondary salinization and other adverse phenomena that contribute to the alienation of hundreds of thousands of hectares of fertile land from agricultural use. The main soil ecological indicators of Greater Caucasus natural and cultivated cenoses were studied. These studies of modern soil cover are of great importance for the development of agriculture in the country. The selected territory of the study is the most important tourist area due to the enrichment of natural vegetation and the beauty of relief landscapes. The obtained results show the differences and similarities in environmental parameters between soil sections. Horizontal and vertical distribution maps showed southern slopes of Greater Caucasus landscapes in Azerbaijan. The statistical parameters of multiple regression analysis of the dependence of plantation productivity on the age and properties of the soil showed deviations in different horizons. Currently, in order to solve the above problems, the creation of interactive electronic soil ecological assessment maps and maps of soils is relevant. The presented work was to study the current state of typical mountain-forest brown, residual carbonate mountain-forest brown and mountain-gray-brown soils formed on the north-eastern slope of the Greater Caucasus, to analyze their morphogenetic horizons of the structure based on the International WRB system and to determine the possibility of their use in agriculture.

3.4 Conclusion

Microscopic mold fungi, the main destructors of organic matter, were found in all the studied samples of gray forest soil, which is due to favorable physicochemical conditions for them: acidic reaction of the environment (pH 5.9), sufficient amount of nutrients (organic content is 4.9–4.7%), and high humidity (23.7–27.9%). At the same time, in the soil of microdepressions on the fallow land, their number is the highest and amounts to 7.0–8.0 thousand CFU/g in the A and A_1 horizons. The maximum number of actinomycetes was found in the virgin gray forest soil on the hillock, where it amounted to 360 thousand CFU/g, which is 5 times more than in the same soil horizon of the depression on the natural soil and 30 times more than in the soils of both elements of the microrelief on the fallow land. In taxonomic terms, micromycetes in the studied gray forest soil are represented by the following dominant species: *Penicillium notatum*, *Penicillium chrisogenum*, *Trichoderma viride*, *Trichoderma lignorum*, *Aspergillus niger*, *Mucor* ssp., *Paecilomyces* ssp., *Crustosum* ssp. Representatives of the genera *Fusarium* and *Monatospora* are rare. As a result of the analysis of the obtained data, the total reserves of organic matter of the secondary spruce forest were determined, which amount to from 21.5 to 32.7 kg·m^{-2}. When small-leaved forests transition to the total biomass of perennial parts of the stand increases, which contributes to the accumulation of organic matter by the ecosystem. The greatest contribution to the accumulation of organic matter by the studied plant communities is made by perennial parts of the forest stand (up to 88%) and litter of the forest stand (up to 15%), which determines the need for a more detailed assessment of these components of forest ecosystems during monitoring observations. The C content of microbial biomass in humus horizons of sod soils ranges from 0.49 to 1.29 mgC/g. Its reserves in the 0–35 cm layer vary from 1.39 to 2.74 tC/ha, which can be assessed as significant for this type of soil. Microbiological and biochemical indicators can be used in assessing technological methods to determine the rational use of gray forest soils.

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CHAPTER 4

Information technologies in scenario-based modeling of post-conflict territory remediation: from express sanitation to sustainable recovery

Bohdan Cherniavskyi

Abstract

The study presents a comprehensive analysis of the application of information technologies in scenario modeling of remediation of post-conflict territories, within the sample of three regions of Ukraine, affected to different degrees and scales by military activity (Kherson, Zaporizhzhia, Kharkiv regions), as a practical case. A hybrid integrated model has been developed by the author and proposed for implementation, combining geographic information systems (GIS), machine learning (ML), optimization algorithms, and other tools of modular deployment of digital infrastructure. The developed remediation model is based on the principle of complementarity, combining traditional and green methods depending on the scenario. Such flexibility ensures the adoption of the most well-founded managerial decisions and accelerates the transition to sustainable recovery. In the study, gradient boosting algorithms and Online ML were used for the purpose of providing predictive modeling and dynamic response in real-time mode. A comparative analysis of remediation scenarios was carried out using digital modeling, KPIs, and predictive algorithms. The results of the modeling confirm the high relevance and practical significance of the triad ML + GIS + IoT, and also demonstrate the viability of the modular remediation system. The author proposed using matrices of validity of digital components and heat maps, which will allow the justified selection of digital solutions; forecasting the risks of their implementation, as well as forming strategies for their phased implementation.

Keywords

Digital management, traditional remediation (TR), green remediation (GR), complementarity, invasion, scenario modeling, geographic information systems (GIS), machine learning (ML), multi-criteria analysis (MCDA), optimization algorithms, express sanitation, sustainable recovery.

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4.1 Introduction

As one can be convinced based on the events of recent years, armed conflicts cause large-scale damage to the environment, creating acute and long-term ecological problems on territories affected by military activity. Thus, for example, the result of military-type activity of the aggressor in Ukraine was damage (in some cases irreparable) estimated at more than 56.4 billion USD, characterized by large-scale pollution of air, water, and soil [1]. About 30% of the territory of Ukraine is littered with unexploded ordnance and mines, and approximately 160 thousand km² of land were subjected to intensive bombardments, in turn forming zones of ecological pollution from destroyed industrial facilities and infrastructure. Tens of thousands of hectares of land require the elimination of contaminants polluting it and remediation of millions of tons of soil. The consequences for ecosystems are acquiring a catastrophic character: soil degradation, pollution of water resources, loss of biodiversity – represent a threat to the health of the population and largely complicate the return of displaced residents to their native lands and the subsequent restoration of economic activity. Thus, sustainable recovery of post-conflict territories becomes an urgent task, on the solution of which depends, above all, national ecological security, as well as the complete revitalization of the regions [2].

The full-scale war in Ukraine caused unprecedented environmental destruction, leading to the contamination of territories requiring both emergency sanitation and long-term remediation. Traditional approaches (such as excavation of soils, thermal treatment, chemical restoration, etc.) often disrupt the ecosystem and can result in negative consequences for it. This determines the need for in-depth comprehensive study of all possible options for the use of available and expedient methods of remediation of soil, water, and air, as well as the creation of digital scenario models capable of adapting and ensuring the transition from express response to long-term sustainable recovery.

This study responds to the modern challenge regarding the necessity of digitalization of environmental recovery programs in zones of armed conflicts.

The aim of the study is the development of a digital scenario model of remediation of post-conflict territories using modern information technologies, ensuring the transition from express sanitation to sustainable recovery.

In accordance with the aim, the following research tasks were identified: in-depth analysis of the theoretical and methodological foundations of remediation of contaminated territories; identification of the features of various remediation scenarios based on the analysis of various types of contamination and based on the prioritization of goals; design of an integrated digital model based on GIS, IoT, ML, and optimization algorithms; evaluation of digital tools using multi-criteria validity matrices and heat maps; development of strategic recommendations for modular deployment of digital infrastructure and replication of the model.

4.2 Theoretical and methodological basis of the research

First of all, it is necessary to outline the contours of the concept "green remediation" (*Green Remediation*, *GR*), by which the author means the use of a set of environmentally sustainable approaches to the cleanup of contaminated territories (soil, water, and air), which minimize the impact on the environment and at the same time contribute to the restoration of natural resources.

The term Green Remediation was first proposed and developed by the Environmental Protection Agency (EPA) in the USA as part of efforts to integrate environmental principles into the processes of cleanup of contaminated lands [3].

Next, the results of an in-depth analysis of the differences of GR from traditional remediation (*Traditional Remediation*, *TR*) will be presented and its key aspects verified. So, a panoramic review of the scientific literature on the specified problem made it possible to identify traditional remediation as a set of technologies and methods aimed at the cleanup of the contaminated environment (soil, water, air) using physical, chemical, and engineering processes.

The basic methods of traditional remediation of military contamination can include the following:

– physical methods, such as excavation of contaminated soil, filtration, sedimentation and flotation of water, as well as the use of barriers to prevent the spread of contamination;

– chemical methods, which include the application of chemical reagents for neutralization or adsorption of pollutants;

– biological methods, such as the use of bacteria, microorganisms, and plants for the decomposition or absorption of contaminants (for example, bioremediation and phytoremediation);

– thermal methods, based on the incineration or heating of contaminated soil or water for the destruction of toxic substances.

As is emphasized in the majority of studies on this topic, the unconditional advantages of the tools and methods of TR are:

– effectiveness and speed of impact, since with the help of traditional remediation tools, as a rule, the set goals are achieved faster, which makes them especially useful in situations requiring immediate intervention;

– predictability of results, which is justified by the better degree of study, and therefore predictability of consequences, and this facilitates the planning and management of remediation projects;

– versatility, which allows the use of TR methods for a wide range of military contamination on one territory, including heavy metals, organic and inorganic substances;

– wide availability of technologies, which is tested and proven in specific conditions, which simplifies the process of implementation of remediation.

However, as was identified by the author, the list of disadvantages of the tools of Traditional Remediation is more extensive than the above highlighted advantages, and this at the very least requires a thoughtful approach to their selection and application. The conclusion reached by the author of the monograph is that traditional methods of remediation, despite their effectiveness in the short term, can carry significant risks in the long term. These risks cover not only environmental consequences, but also affect genetic, social, economic, and medical aspects, which emphasizes the necessity of thorough analysis and planning before their application. It is about the so-called "*ecological footprint*", which means the totality of the negative impact of these methods on the environment in the process of elimination of military contamination.

Taking into account the scale and complexity of remediation activities carried out within the framework of the implementation of the remediation strategy of Ukraine, it is especially necessary to consider its *invasiveness*, by which the author of the scientific work means the type of anthropogenic intervention which, despite its focus on the restoration or improvement of the state of the ecosystem, can lead to deep and long-term negative changes, often of an irreversible nature.

Among the key disadvantages it is necessary to highlight:

– the high risk of irreversibility of changes in the ecosystem, which consists in the disruption first of the structure of the system, and then of the eco-balance, the process of restoration of which may take decades or even centuries, if this is possible at all [4, 5];

– high risks from the use of several TR methods simultaneously on one territory. For example, simultaneous chemical treatment and thermal neutralization of soil or water can lead to unpredictable chemical reactions, creation of secondary pollutants, and additional environmental threats [6, 7];

– risk of secondary contamination, which consists in that the application of chemicals can lead to the formation of by-product pollutants, and this, in turn, leads to the necessity of further treatment of secondary waste and an increase in remediation costs [8, 9];

– high cost and high energy consumption, since the use of specialized equipment with material costs in the process of its application can make traditional remediation very expensive, especially on large territories.

In scientific publications of recent times, as the author of the study has identified, publications still prevail that are focused on the application of sustainable and environmentally clean methods of remediation, such as "green remediation", which includes the use of natural processes for the cleanup of contaminated territories. For example, in a comprehensive study on the application of remediation of contaminated lands, the authors emphasize that the choice of technology is no longer based exclusively on the elimination of the source of contamination, but is aimed at the restoration of soil quality. Thus, "green remediation" can be the key to solving the problem of restoring contaminated sites, since it focuses on the quality of the environment, including the preservation of the biocenosis. Further developments in the field of green remediation reflect the goal of promoting cleanup strategies that also take into account the consequences of climate change [10].

In addition to the above-mentioned method, among the most popular methods of "green remediation" are: phytoremediation, bioremediation, the use of microalgae, biofiltration, air biofiltration, and others. Specifically, on each of the listed methods of GR a large number of publications has been published, which allowed the author to identify the main advantages of these methods in comparison with traditional methods of cleanup of contaminated territories. Here are the main ones:

– environmental friendliness, since in such natural processes as plant growth and microorganism activity the impact on the environment is minimal;

– economic efficiency, which is expressed in that plants and microorganisms can perform the cleanup work over a long period of time with minimal maintenance costs;

– improvement of the state of the ecosystem, since plants and microorganisms not only clean the soil or water, but also improve its structure, contribute to the preservation of biodiversity, and prevent erosion;

– generation of additional multifunctional ecosystem effects: plants and microorganisms used for the purposes of GR can realize, along with the main function, additional ones, such as compensation of the carbon footprint, enrichment of the lands with humus, destruction of complex forms of decomposable military activity waste, which brings additional benefit to the ecosystem and society as a whole [11].

The parametric comparative analysis of traditional remediation approaches and methods of "green remediation" is presented in **Table 4.1**.

According to the author's conviction, traditional remediation (TR) can be characterized as an "invasion" (from Latin *invasio*) due to its aggressive impact on ecosystems, including destruction of soil structure, change of hydrology, creation of secondary pollutants, destruction of the biocenosis. In contrast to this, green remediation (GR) acts as a "regenerative" approach, minimizing the ecological footprint and contributing to the restoration of ecosystems.

Table 4.1 Parametric assessment of methods of traditional and green remediation of soil, water, and air

Parameter	Traditional remediation	Green remediation
Soil remediation		
Technologies	Excavation, thermal neutralization, chemical treatment	Phytoremediation (use of plants), bioremediation (microorganisms)
Environmental impact	High (disruption of the ecosystem, greenhouse gas emissions)	Low (minimal intervention in the ecosystem)
Cost	Usually high due to costs of equipment and materials	Usually lower, but depends on duration and methods
Execution time	Fast, but temporary solutions often require subsequent measures	Long-term (from months to several years), requires monitoring
Energy consumption	High due to the use of heavy machinery and equipment	Low, based on natural processes
Water remediation		
Technologies	Chemical precipitation, filtration, sorption	Biofiltration, bioremediation (use of microbes and plants)
Environmental impact	Medium (may include the use of chemical reagents)	Low (use of natural cleaning methods)
Cost	High due to the application of complex technologies and chemicals	Usually lower, except in cases of long-term monitoring
Execution time	Fast, but requires constant control and replacement of filters	Depends on natural processes, may take more time
Energy consumption	High, requires energy for operation of equipment	Low, natural processes work on solar and biomass energy
Air remediation		
Technologies	Adsorption, thermal oxidation, chemical restoration	Biofiltration, use of vegetation for absorption of pollutants
Environmental impact	Medium, may include emissions from cleaning installations	Low, based on natural processes
Cost	High, requires complex technologies and constant maintenance	May be lower, especially when using vegetation
Execution time	Fast, but requires regular maintenance	Long-term processes, but more sustainable
Energy consumption	High, equipment requires constant operation	Low, based on natural processes

In the conditions of a post-conflict landscape, especially in the presence of: threats to the life and health of the population (explosive ordnance, chemical contamination); critically damaged infrastructure (water supply systems, sewerage, transport); acute necessity for sanitary isolation (for example, in case of flooding or spread of pathogens); the application of traditional methods of remediation (TR) may be not only justified, but also inevitable. However, such methods are accompanied by a significant ecological footprint, as was already mentioned above.

Invasiveness, in the author's view, is always associated with an increase of the ecological footprint, but in the scenario management model this is perceived as a controlled risk, compensated by: rapid localization of the threat; reduction of secondary risks (for example, delayed migration of pollutants); the possibility of the fastest transition to restorative, GR-oriented measures.

Thus, it appears fully logical and expedient to substantiate the concept of the I-S-R cycle (invasion–stabilization–restoration) as a phase model of digital management of remediation, where each stage corresponds to certain strategic tasks, the choice of which is based on scenario analysis of threats and opportunities.

This cycle allows the formation of an adaptive logic of management, in which both traditional (TR) and green (GR) methods of remediation are used in a complementary model. The ambivalence and complementarity of TR and GR are conditioned by:

– the difference of goals by phases of the I-S-R cycle: TR – elimination of critical threats (invasion), GR – creation of conditions for sustainable recovery (regeneration);

– the difference of methods and approaches: TR is aggressive and radical, GR is gentle and nature-oriented;

– the difference of consequences: TR can worsen the state of the ecosystem in the long-term perspective, GR – restore and improve.

At the same time, the complementary combination of TR and GR in an integrated model allows the implementation of optimal scenarios, where TR ensures rapid elimination of acute risks, and GR ensures long-term sustainability and ecological safety.

In the context of this study, the focus of the author's attention was concentrated on the in-depth study of the book "Natural resources and post-conflict assessment, remediation, restoration, and reconstruction: Lessons and emerging issues" [12]. The authors of the study emphasized the assessment of remediation of post-conflict territory, which demonstrates obtaining tangible benefits, in particular, the restoration of resource stability, including the improvement of the population's standard of living, state revenues, creation of new jobs, as well as the expansion of opportunities for business development.

The author's position consists in that the multiplicative effect of remediation of territory lies in the comprehensive impact of recovery activities aimed at improving the ecological balance, which as a result allows launching a cascade of chain reactions and positive changes affecting various aspects of socio-economic, ecological, and even political life of the region (both domestic political and foreign political).

This happens due to the fact that the improvement of the ecological condition of the territory makes it more attractive for the life of the population, development of economic activity, infrastructure, tourism, and inflow of investments. Thus, a healthy ecosystem ultimately stimulates the revitalization of territories affected by military activity. This leads to the creation of new jobs, an increase of tax revenues, growth of budget income at all levels, and as a result, an increase of national competitiveness.

Visually, the multiplication effect can be presented in the form of circles on water: one change (in our case, this is remediation of the ecosystem) creates waves spreading far beyond the epicenter of impact. Similar to circles on water, the multiplicative effect of remediation spreads to various spheres (social, economic), creating cascading positive changes that gradually cover ever wider areas, improving the condition and well-being of the entire territory as a whole. For example, the scientists K. Williams and J. Hoffman in their study describe a similar effect in the form of feedback chains [13].

Thus, various approaches to remediation can generate a cascading reaction of positive changes in each of the spheres (ecological, social, economic) and influence the sustainable development of the territory, namely:

– green methods of remediation produce a more pronounced multiplicative effect, especially in the long-term perspective, impacting all three spheres of influence in the mode of permanent transformation;

– traditional methods are recommended and effective for rapid elimination of problems – "*express sanitation*" but their influence on the long-term multiplicative effect is limited, especially in the social and economic spheres.

In the view of the author of this scientific work, the main goal of "*express sanitation*" is the rapid elimination of environmental risks and prevention of their scaling. This makes it possible in a short time to stabilize the situation and prevent further damage, which is critical in conditions affected by military activity or technogenic disasters. "Express sanitation" using radical tools of traditional remediation is recommended in situations where immediate intervention is required; however, it does not provide for a strategic goal in the form of deep restoration of ecosystems or permanent transformation of the socio-economic situation. In the long-term perspective, such territories often need additional remediation using green methods for the purpose of sustainable recovery.

In the author's conviction, a complementary combination of traditional methods (TR) and green methods of remediation (GR) can become an effective strategy for achieving both short-term and long-term recovery goals of Ukraine after the end of active military actions. The possibility of applying a combined approach will allow the rapid elimination of the most critical threats, and then ensure the sustainable recovery of ecosystems and the territory as a whole. The unconditional advantage will be that such an approach, in addition, strengthens the multiplicative effect: express sanitation allows the elimination of the most significant and negatively influencing contamination, protecting the population and creating conditions for economic activity, and at the subsequent stage green remediation generates long-term benefits, contributing to the creation of sustainable economic opportunities, such as, for example, ecotourism or agriculture [14] (**Fig. 4.1**).

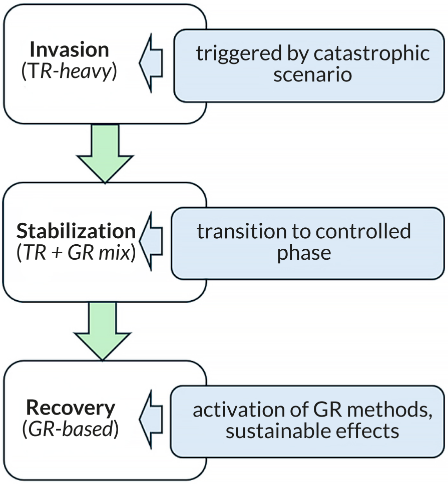

Fig. 4.1 Analytical scheme of the Invasion-Stabilization-Recovery (I-S-R) cycle

The multiplication effect is repeatedly described by the author of this study in a number of scientific works [15, 16]. The multiplicative effect arising as a result of the implementation of remediation activities with the involvement of TR and GR methods in the context of the issues of this study represents a reflexive (impulse) dynamics of positive cascading changes covering the ecological, economic, and social spheres of life of post-conflict territories, which in the long term leads to their complete revitalization. The hypothesis of the author of this scientific work consists in that the developed and then implemented digital model of remediation will possess the same property. Namely: the ability of the digital integrated model to generate a chain reaction of positive changes into a single end-to-end digital amplification through the transformation of local results into a systemic sustainable effect, creating a basis for sustainable socio-economic post-war development of the territory.

The benchmarks described below demonstrate the successful application of combinations of TR and GR, emphasizing their complementarity in achieving short-term (express sanitation) and long-term (sustainable recovery) goals:

1. *Kosovo.* Thus, after the military conflict in Kosovo, combinations of soil excavation (extraction) and subsequent biorecultivation were applied for the cleanup of contaminated sites, which as a result made it possible to restore land for agricultural use [17, 18].

2. *Vietnam.* Phytoremediation was used after chemical treatment for the cleanup of land contaminated with dioxin from "Agent Orange". As is known, this is a herbicide that was used by the US army during the Vietnam War to destroy foliage and forests. It contained dioxin, which is poisonous and has a long-term negative impact on human health and the environment [19].

3. *Kuwait.* After the end of the Gulf War, projects for the remediation of oil-contaminated soils in Kuwait included traditional methods, such as skimmers for oil removal, and biorecultivation using compost and microorganisms, which contributed to the restoration of desert ecosystems and the reduction of hydrocarbon content [20, 21].

4. *Nigeria.* After oil spills in the Niger Delta, combinations of contaminated soil excavation and bioremediation using microorganisms were applied for the cleanup of oil-contaminated soils, which made it possible to partially restore land for agricultural use and improve the ecological condition of the region [22, 23].

Unlike Kosovo and Vietnam, the contamination in Nigeria and Kuwait is mainly associated with oil production, and not with military actions, however, with certain reservations, they can also be considered benchmarks. It should be noted that their environmental consequences (oil spills, soil and water contamination) are similar to those observed in post-conflict zones such as Ukraine, where military actions caused oil contamination and other environmental problems.

The integrated remediation model combining TR and GR makes it possible to achieve a balance between efficiency (cleanup speed, percentage of pollutant removal) and rationality (minimization of costs and ecological footprint). Successful benchmarks, such as combined remediation in Kosovo (extraction + bioremediation), in Kuwait (skimmers + bioremediation) and in Vietnam (chemical treatment + phytoremediation), demonstrate the possibility of integration [24]. Computer modeling, including GIS and ML, can optimize the choice of methods by predicting their impact on ecosystems and socio-economic indicators [25].

Thus, the integrated remediation model precisely due to the properties of optimal complementarity, synergistic and multiplicative effect of TR and GR methods, as well as the variable possibility of choice, represents a powerful tool for solving complex environmental problems, especially in post-conflict zones such as Ukraine. By combining the rapid action of traditional methods with the sustainability of green methods, it will be able to ensure the environmental safety of territories in the short term and their subsequent recovery for long-term use.

4.3 Development of an integrated remediation model (TR and GR) using computer modeling for the purposes of sustainable recovery of post-conflict territories

This section reveals the structure and logic of building the integrated model and is the next logical step in the study, focusing attention on its functional elements and synergistic effect. The development of the integrated remediation model using computer modeling is aimed at the formation of a scientifically substantiated approach to the sustainable recovery of post-conflict territories. Such an approach, as was described earlier, makes it possible to optimally combine traditional and green remediation technologies (TR and GR) into a single complementary system taking into account the complex spatial-temporal dynamics of contamination. At the basis of the model lies the formalization of key components and the use of digital technologies (ML, IoT, GIS), which ensures adaptability and optimization of managerial decisions in conditions of high uncertainty (**Table 4.2**).

Thus, the developed integrated complementary model takes into account the synergy of traditional and green remediation methods with optimal use of digital components. Each component of the model is reasonably substantiated and plays its necessary role in achieving the goals of the study:

– input parameters provide a comprehensive description of contaminants of the contaminated territory and specific conditions;

– remediation methods support the combined unity of TR and GR methods;

– the objective function optimizes the balance between criteria;

– the ML model predicts effectiveness taking uncertainty into account;

– monitoring allows adaptation to dynamic conditions of the external and internal environment.

It is necessary to emphasize the strengths of the developed formalization, namely:

1. Complexity – the model takes into account all key aspects (ecological, technical, social), which makes it relevant for different phases of the I-S-R cycle.

2. Multicriteriality – the use of the objective function allows adapting priorities to different scenarios (express sanitation, sustainable recovery).

3. Hybridization of TR and GR – the architecture of complementarity of methods is embedded, which ensures compliance with the phases of the I-S-R cycle: TR $\to$ invasion; TR + GR $\to$ stabilization; GR $\to$ recovery.

4. Online adaptation – real-time monitoring, which allows correcting the model depending on the dynamics of contamination and the course of implementation of remediation activities.

Table 4.2 Formalization of the integrated remediation model

Components	Model formalization
Input parameters	$Z = \{z_1, z_2, ..., z_n\}, z_i = (t_i, c_i(t), A_i, L_i, r_i, \tau_i, e_i, s_i)$, $t_i \in T$ – type of contamination (including unexploded ordnance, heavy metals, petroleum products, radionuclides and others); $c_i(t) \in R^+$ – concentration taking into account temporal dynamics; $A_i \in R^+$ – remediation area; $L_i \in R^2$ – contamination coordinates; $r_i \in [0,1]$ – risk range; $\tau_i \in R^+$ – time period since contamination; e_i – ecological characteristics of resources (soil type, pH, hydrology and others); s_i – socio-economic characteristics (proximity to population, land value and others)
Remediation methods	$M = M_{TR} \cup M_{GR}$. For each remediation method $m_j \in M$: effectiveness $E_{ij} = f(t_i, c_i(t), \tau_i, e_i, m_j, S_i)$; cost C_{ij}, including expenses of method m_j; ecological footprint LCA_{ij}; application time of method $m_j T_{ij}$; risk of secondary contamination r_{ij}^{sec}
Objective function	$\max_{S_i \subset M} \lambda_1(\phi) \cdot \frac{Eff(S_i)}{E_{\max}} + \lambda_2(\phi) \cdot \left(1 - \frac{\sum_{j \in S_i} LCA_{ij} + r_{ij}^{sec}}{LCA_{\max}}\right) + + \lambda_3(\phi) \cdot \frac{M_{eff}(S_i)}{M_{\max}} - \lambda_4(\phi) \cdot \frac{C_{ost}(S_i)}{C_{\max}}$. Constraints: $\sum_{j \in S_i} C_{ij} \le B_i, \sum_{j \in S_i} T_{ij} \le T_{\max}, E_{ff}(S_i) = g\left(\sum_{j \in S_i} E_{ij} w_j, S_i\right)$ – nonlinear function that allows accounting for synergy of TR and GR methods; $M_{eff}(S_i)$ – obtained multiplicative effect; $\lambda_i(\phi)$ – weights determined using ML
ML model	$X = \{(t_i, c_i(t), \tau_i, A_i, r_i, v_i, e_i, s_i, S_i)\}, y = E_{ij}^{fact}, \hat{E}_{ij} = Gradient\ Boosting\ (X; \theta)$, sources of data – IoT, GIS, satellite images, data of similar territory recovery projects; accounting for uncertainty – Bayesian methods or ensembles. Gradient boosting is chosen for its ability to handle complex nonlinear dependencies and heterogeneous data, which corresponds to the tasks of ecological modeling
Monitoring and adaptation	Observed contamination $\theta_{i,t} = (c_{i,t}, r_{i,t}, M_{eff,t})$, Forecast error $\in_{i,t} = \lvert \hat{\theta}_{i,t} - \theta_{i,t} \rvert$. ML Model$_{t+1}$ = Online Gradient Boosting (ML Model$_t$, $\in_{i,t}$, Data$_{IoT, GIS}$) – online learning is suitable for real time, model updating using new IoT and GIS data, which as a result ensures adaptability

4.4 Simulation scenario modeling

Simulation scenario modeling of contaminated territories makes it possible to predict the dynamics of contamination, assess the forecasted effectiveness of the methods of remediation planned for application, and optimize resources for the ecological recovery of the territory. In the context of the current situation in the regions of Ukraine, reflected in **Fig. 4.2**, the predominant part of the country's regions is contaminated with unexploded mines, explosives, petroleum products, heavy metals, and other toxins. In this situation, modeling becomes a critically important and significant tool for crisis management, elimination of environmental risks, and negative consequences associated with ongoing military activity.

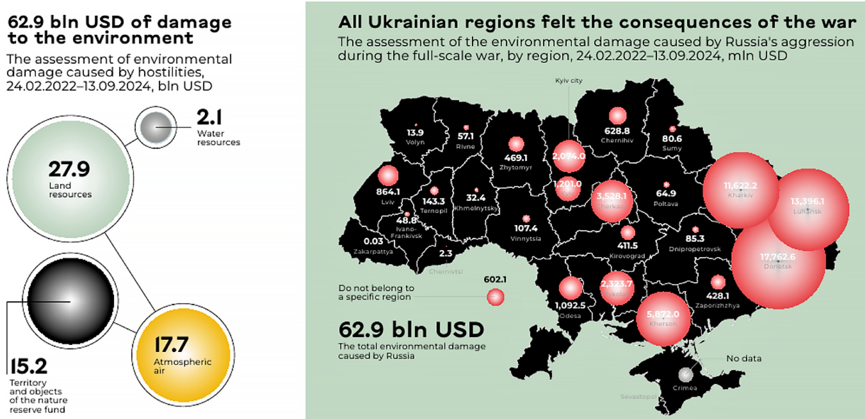

Fig. 4.2 General and regional assessment of the consequences of the war from 24.02.2022 to 13.09.2024
Source: [26]

For conducting simulation modeling the author selected three regions of Ukraine: Kherson region (eco-catastrophe due to the blowing up of the Kakhovka HPP), Zaporizhzhia region, city of Enerhodar (ecological danger of the nearby Zaporizhzhia NPP), and Kharkiv region (destruction of industrial facilities, contamination of soil and water resources). These regions reflect diverse types of environmental threats caused by military actions, but all of them have strategic significance for Ukraine. Below is presented a detailed analysis of the justification of the selection of the regions, as well as an assessment of the risks and significance of the modeling (**Table 4.3**).

The validity of the integrated model developed by the author was determined by the method of multi-criteria analysis (MCDA), using aggregated data on the accuracy of ML model forecasts, expert assessments, and data coverage coefficients by regions (**Table 4.4**). The average validity ≈ 64.8%, which is scientifically justified for the stage of pilot testing. It should be noted that in international practice (such international projects as UNEP, EPA, CEOBS, INSIDE Model) for systemic models in post-conflict ecology, validity of 65–80% is considered adequate for the pilot level, provided that the model is adapted in the process of operation.

Table 4.3 Scientific justification of the selection of regions for scenario modeling

Fundamental characteristics	Description
1	2
Kherson region	
Types of contamination	Petroleum products, heavy metals, chemicals (pesticides, fertilizers) washed away from flooded warehouses correspond to the parameter t_i of the model. The dynamics of concentration $c_i(t)$ require accounting for the migration of contaminants into groundwater and the Black Sea
Ecological characteristics	Chernozems, high fertility, proximity to the Dnipro and the Black Sea make the region critically important for agriculture. Loss of irrigation threatens desertification of 584 thousand ha of land
Risks	High risk to health (contaminated water), food security, and ecosystems (disruption of food chains)
Significance of modeling	The selection of Kherson region is justified by the scale of the environmental disaster, the diversity of contamination, and the strategic importance for agriculture. The environmental consequences of the blowing up of the Kakhovka HPP dam include contamination of soil and water with petroleum products, chemicals, death of biological resources (11 tons of fish), desalination of the Black Sea, and the loss of 94% of irrigation systems in the region. Modeling will make it possible to optimize remediation, minimize the ecological footprint, and restore food security [15]
Zaporizhzhia region	
Types of contamination	Probability of contamination with radionuclides (cesium-137, strontium-90), heavy metals from ammunition, chemicals from damaged infrastructure. A potential accident at the ZNPP could lead to radioactive contamination over an area up to 30 thousand km²
Ecological characteristics	Lowering of the level of the Kakhovka reservoir threatens the cooling system, and sandy soils of the region contribute to the migration of radionuclides
Risks	Catastrophic risk of a nuclear accident (comparable to Chernobyl), threat to the health of millions of people and long-term contamination not only of Ukraine but also of EU countries

Continuation of Table 4.3

1	2
Significance of modeling	The region is critical due to the nuclear threat and the dependence of southern Ukraine on water supply. Modeling will make it possible to develop preventive measures and remediation plans in case of an accident, which is relevant for international security
	Kharkiv region
Types of contamination	Heavy metals (including lead, cadmium), petroleum products, explosives (including TNT, RDX), as well as phosphorus from ammunition. The dynamics of $c_i(t)$ are complicated by the possibility of migration of contaminants into water bodies
Ecological characteristics	Predominantly chernozem and forest-steppe soils of the region are quite sensitive to the listed types of contamination, and the rivers of the region are part of the Don basin, which potentially can negatively affect the ecological situation of neighboring regions
Risks	High risk to health (contaminated water and soil), threat to food security (contamination of agricultural land) and ecosystems (disruption of aquatic ecosystems) [27]
Significance of modeling	Kharkiv region, as an industrial center, suffered from the destruction of factories, warehouses, and infrastructure, which led to contamination of soil with heavy metals, ammunition (including lead, TNT), petroleum products, and chemicals. Water resources, including the Siverskyi Donets and Oskil rivers, are contaminated with discharges and toxins. Kharkiv region represents a typical case of industrial and military contamination, which makes it suitable for testing the model on complex scenarios. Recovery of the region is critical for the economy and security of Ukraine

Table 4.4 Testing of the integrated remediation model by regions: Kherson, Zaporizhzhia, and Kharkiv regions

Regions	Validity (%)	Data sources	Data limitation	Correspondence to I-S-R scenario
Kherson	67.1	Satellites (Sentinel, Landsat), IoT (pointwise), laboratory analyses of water and soil	Limitation of real-time monitoring, lack of IoT networks	High at phases I (TR) and S (TR + GR), moderate at R (GR)
Zaporizhzhia	53.4	IAEA, satellites, partially drones (demining)	Low availability of monitoring data, shortage of ecological data on radiation levels	Good at phase I (TR), weak at S (TR + GR) and R (GR)
Kharkiv	73.8	Satellites, laboratory analyses of soil and water, GIS mapping	Lack of comprehensive information about the ecological situation in the region, no full IoT network	Excellent at phases I and S, good at R

In the opinion of the author, digital management of remediation of post-conflict territories requires the application of tools that allow systemic assessment and selection of IT solutions. Within the framework of this study, two types of validity matrices of digital components in the form of heat maps were developed and tested:

1. A universal matrix, which is built in the context of key criteria, such as adaptability, feasibility, strategic priority, cost-effectiveness, environmental impact.
2. Regional I-S-R matrices, oriented towards the implementation of remediation scenarios taking into account the specifics of territories (Kherson, Zaporizhzhia, Kharkiv regions).

For these purposes, a list of key digital components (IoT, ML libraries, GIS, server solutions and others) relevant for remediation scenarios was compiled and grouping of components by functional blocks was carried out (**Fig. 4.3**). Further, evaluation criteria were identified (in particular: adaptability, feasibility, ease of implementation, strategic priority, cost-effectiveness, environmental sustainability), as well as weighting coefficients of the criteria, which were selected taking into account the scenarios (express sanitation, long-term recovery, hybrid approaches). Then, based on data of expert evaluation of digital components from open sources and normalization, information was collected and aggregated (on a scale from 1 to 5). Then the scores were normalized according to regional and scenario features.

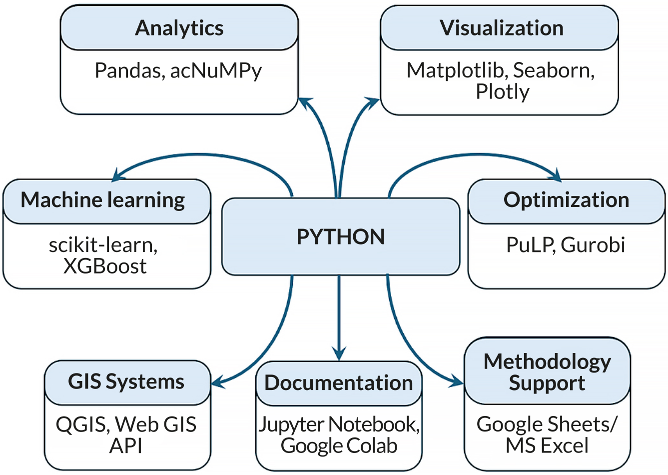

Fig. 4.3 Compositional ensemble of software and digital tools for remediation modeling

Thus, the validity matrix can act as a universal visual analytical tool that displays the comparative applicability of digital components according to a multitude of criteria (including in terms of adaptability, feasibility, ease of implementation, strategic priority, cost-effectiveness, as well as level of impact).

In the conviction of the author, the combination of two types of matrices forms the basis of adaptive digital management of remediation, allowing consideration of goals of different scale (sustainable recovery at micro- and meso-levels, national security), as well as micro-level tasks (elimination of local threats, stabilization of zones of ecological disaster) (**Fig. 4.4**, **4.5**). This will make it possible: to reasonably select digital solutions; to foresee in advance risks and complexities of implementation (for example, high cost or low adaptability of certain digital components); to form strategies for phased implementation from the basic level (QGIS + Python + River) to advanced (Gurobi + DGX Clusters); to substantiate funding requests by highlighting the most priority and effective components.

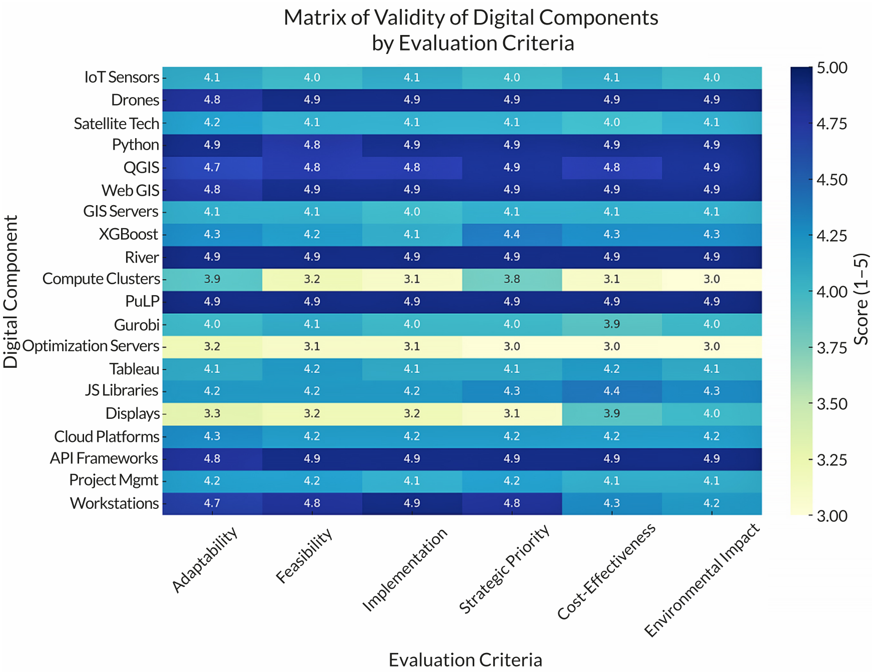

Fig. 4.4 Matrix of validity of digital components by evaluation criteria

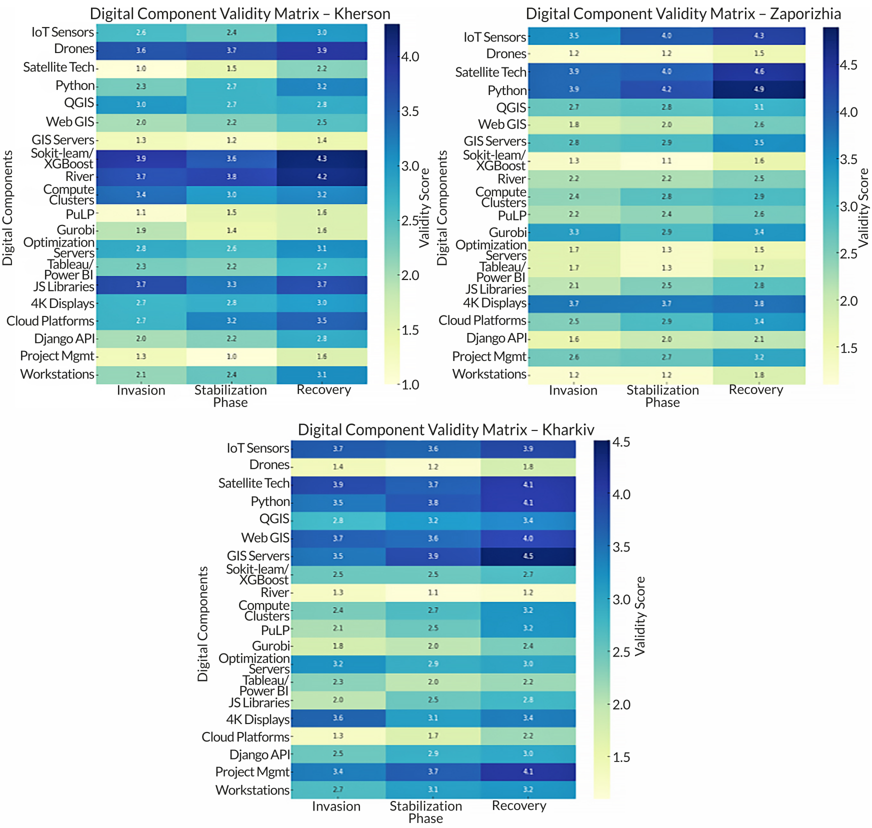

Fig. 4.5 Comparative heat maps for Kherson, Zaporizhzhia, and Kharkiv regions

The general conclusions reached by the author of the study are as follows: regarding the complementarity of the approach – at the invasion phase there is a priority for digital components providing speed (TR-focus), and at the recovery phase – for components that allow making sustainable decisions and optimally integrating them (GR-focus); regarding region-specificity – Zaporizhzhia region requires greater emphasis on radiation monitoring, Kherson – on hydro-ecological control, Kharkiv – on soil restoration and mine clearance; regarding the increase of adaptability of the integrated model proposed for implementation – digital components demonstrate flexibility in application by phases and make it possible to build scenario-justified remediation management.

4.5 Conclusion

The results obtained from the conducted study confirmed the achievement of the set goal – the development of a digital scenario model for the remediation of post-conflict territories, ensuring the transition from express sanitation to sustainable recovery based on modern IT solutions. The author developed an integrated architecture of digital management, adapting to the phases of Invasion-Stabilization-Recovery (I-S-R), where the key term becomes invasion – as a scientifically justified designation of the initial stage of acute anthropogenic intrusion, including military consequences for ecosystems. The proposed adaptive model of digital remediation for implementation combines methods of systems engineering, agent-based approach, and digital transformation through the application of: GIS for mapping environmental threats, IoT for real-time monitoring, ML/AI for scenario-based forecasting and multicriteria optimization. A pilot testing of the model was conducted in three strategically important regions of Ukraine (Kherson, Zaporizhzhia, and Kharkiv regions), with the identification of regional features and recommendations within the framework of selecting priority remediation measures: for Kherson region – priority is given to regular hydroecological monitoring, especially IoT networks for tracking the migration of contaminant pollutants in the region's water resources; for Zaporizhzhia region – emphasis on regular radiation monitoring and the development of preventive measures in case of an accident at the Zaporizhzhia Nuclear Power Plant; for Kharkiv region – the necessity of mapping contaminated areas using GIS and drones, followed by large-scale soil remediation, mine clearance, and elimination of pollutants in water bodies. For the purposes of operational remediation management, the author formed and proposes to use validity matrices (both universal and regional) in the form of heat maps. These will make it possible to assess the applicability of digital solutions across a number of criteria (adaptability, feasibility, environmental sustainability, etc.), as well as to visualize and select priority digital components in a regional context.

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CHAPTER 5

Sustainable development policy for post-conflict recovery in Ukraine: the role of environmental indicators in decision-making

Viktoriia Petrenko
Alla Karnaushenko
Kateryna Melnykova

Abstract

This study explores the role of environmental indicators in guiding managerial decision-making for the sustainable recovery of de-occupied territories in Ukraine. The research is grounded in a large-scale survey conducted across 42 territorial communities in southern Ukraine that experienced severe destruction due to the full-scale invasion. The methodological framework is based on sociological data from over 16,000 residents, used to calculate five key environmental indicators: Technogenic Pollution from Military Activity (TPMA), Degradation of Natural Ecosystems and Soil (DNES), Infrastructure and Household War Impacts (IHWI), Access to Natural Resources (ANR), Biosecurity and Public Health Protection (BPHP). The results were visualized using a heat map to identify ecological "hotspots" and prioritize zones requiring urgent intervention.

Particular attention is given to the development of a structural decision-making model that illustrates the progression from problem identification to the implementation of recovery strategies at the local level. The paper proposes actionable directions for response, including environmental monitoring, land reclamation, waste management, and ecological awareness initiatives. It also discusses potential funding sources for environmental initiatives, ranging from international donor programs and national funds to public-private partnerships and innovative financial instruments.

The findings offer practical value for evidence-based environmental policymaking in post-conflict settings, the formulation of localized sustainable development strategies, and the strengthening of institutional capacity at the community level.

Keywords

Sustainable development, environmental indicators, de-occupied territories, post-conflict recovery, decision-making, survey research, environmental policy, project financing, circular economy.

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5.1 Introduction

The issue of sustainable development becomes particularly relevant in the context of post-conflict recovery in territories severely affected by war. Armed conflicts not only result in human casualties and economic losses but also inflict significant environmental damage, exacerbate the vulnerability of social systems, and undermine institutional governance structures. Under such conditions, the achievement of the Sustainable Development Goals (SDGs) – including environmental security, social equity, and economic resilience – requires a rethinking of traditional recovery approaches.

Post-war reconstruction efforts cannot be limited to rebuilding infrastructure or restoring economic functionality. Recovery policies must address interdisciplinary challenges that integrate environmental, social, and governance dimensions. Key priorities include ecosystem restoration, access to clean water, waste management, soil rehabilitation, and the prevention of further environmental degradation. These challenges are not merely humanitarian; they are strategic in terms of national security, stability, and long-term development.

In the Ukrainian context, particularly in de-occupied territories of the southern regions, there is a critical need for an environmentally oriented recovery policy grounded in evidence – namely, environmental indicators, risk assessment, and public engagement. The role of local communities, municipal authorities, and international partners is decisive in this process. Therefore, investigating how environmental factors are incorporated into sustainable development decision-making processes is essential for both scholarly inquiry and practical application.

Integrating environmental considerations into territorial development governance is a prerequisite for achieving long-term sustainability in post-conflict recovery. Policy development and implementation at both the local and national levels must account not only for economic and social factors but also for an objective evaluation of environmental conditions. Environmental quality directly affects public health, agricultural productivity, access to natural resources, and the overall investment attractiveness of a region.

Environmental concerns must be an integral component of local socio-economic development programs. Neglecting them risks creating new sources of social tension and increasing ecological vulnerabilities. In the aftermath of war, ecosystems are profoundly altered – from water contamination to soil degradation and deforestation. These changes disrupt natural balances and complicate reintegration and development processes.

Environmental indicators – such as air and water quality, soil contamination levels, and waste accumulation – serve as critical reference points for decision-making in infrastructure planning, public health, agriculture, and land management. Systematic monitoring and incorporation of these indicators into planning processes help prevent environmentally unsound decisions, increase governance transparency, and lay the groundwork for effective environmental policy.

In post-conflict settings, environmental data becomes even more crucial as a tool for building trust between citizens and authorities, and as a foundation for attracting international aid and investment. Therefore, the environmental dimension must be viewed not as a secondary consideration, but as a foundational element of strategic governance for community recovery in the post-war period.

Despite widespread recognition of the importance of environmental components in local sustainable development strategies, research focusing specifically on the role of environmental indicators in post-conflict recovery remains fragmented and insufficiently systematized. The academic discourse is predominantly oriented toward infrastructure and economic reconstruction [1–5], while environmental concerns are often treated as secondary or disconnected from the broader governance framework.

This gap is particularly pronounced in the Ukrainian context [6–12], where armed aggression has resulted not only in a humanitarian crisis but also in unprecedented environmental degradation. However, existing studies rarely examine how environmental indicators are utilized to inform decision-making at the local level – from resource allocation to regional development priorities. Most recovery programs lack a unified methodology for environmental monitoring or sustainability-oriented impact assessments [13, 14].

Moreover, there is no comprehensive database enabling the analysis of ecological dynamics in de-occupied areas. The potential for engaging citizens in the collection and interpretation of environmental data through civic science approaches remains underexplored, despite its critical importance for transparent decision-making and enhancing trust in local governance.

These shortcomings underscore the need for interdisciplinary research that combines environmental analytics, public administration tools, and sociological data collection methods. Only through such an integrated approach can effective, environmentally sound recovery policies be developed – policies that address real community needs while contributing to the revitalization of local ecosystems.

Given the current challenges posed by military aggression and the urgent need for territorial recovery, this study aims to identify the potential and actual use of environmental indicators in the formulation and implementation of sustainable development policies in Ukraine's de-occupied regions. Considering the scale of ecological loss, objective assessment of environmental conditions must form the basis for decisions that combine short-term stabilization with long-term development goals.

The research focuses on the extent to which environmental indicators – such as air and water quality, soil conditions, access to natural resources, pollution levels, and the availability of waste processing infrastructure – are integrated into local and regional strategic planning. Special attention is given to empirical data from a population survey conducted in de-occupied communities in southern Ukraine, particularly in Kherson and Mykolaiv regions. This allows for the evaluation of public perceptions of the environmental situation and levels of trust in environmental policies implemented by public authorities.

Given the strategic importance of sustainable development for post-conflict recovery, the study seeks not only to assess the current state of affairs but also to outline pathways for improving institutional mechanisms for evidence-based decision-making. The search for a balanced approach – one that integrates environmental, social, and economic dimensions to ensure effective resource management, ecosystem restoration, and risk mitigation – is at the core of this research.

5.2 Research methodology

This study was conducted as part of the project "Stimulating the Development of De-Occupied Territories through Investment and Innovation Tools within the European Union Framework", supported by the EURIZON – Grants for Remote Research program. The project aims to develop evidence-based strategic recommendations for local authorities, investors, and international partners regarding the sustainable and environmentally oriented recovery of Ukraine's de-occupied territories.

Data collection was carried out through an online survey administered via a custom-designed questionnaire in Google Forms between June and September 2024. The target respondents included residents and internally displaced persons (IDPs) who either currently reside or have lived in the de-occupied areas of Mykolaiv and Kherson regions. Participation was voluntary, anonymous, and open-access, ensuring compliance with ethical standards in research. Invitations were disseminated via social media, partner NGOs, community chats, educational institutions, and email distribution lists.

The sampling frame encompassed 42 territorial communities that were liberated in the Mykolaiv and Kherson regions. A total of 16,000 respondents participated in the survey, averaging approximately 380 participants per community. The sample included adult residents who lived in the liberated territories at the time of the survey. The socio-demographic composition was diverse, including individuals of different genders, age groups, and professional backgrounds. Initial analysis confirms that both residents who remained during the occupation and those who returned post-liberation were represented, allowing for a wide spectrum of perspectives on environmental issues. The selection of 42 communities was driven by the project's geographic scope, which focused on the areas most severely affected by the armed conflict in southern Ukraine. Consequently, the sample is reflective of public perceptions regarding the environmental situation and challenges within these communities.

The main research instrument was a structured questionnaire developed by the authors, consisting of eight thematic sections. Section 4, titled "Environmental Situation", was of particular relevance to the study. It included questions aimed at assessing the post-liberation environmental conditions and quality of life in the respective communities. The survey instrument focused on five core thematic areas aligned with key environmental indicators:

1) technogenic pollution resulting from military operations;

2) degradation of natural ecosystems and soil;

3) infrastructural and domestic consequences of war;

4) access to natural resources;

5) biosecurity and public health protection. Each thematic area was represented by one or more questions.

Respondents were asked to assess the presence and severity of issues in these domains (e.g., chemical contamination of soil or water, scale of forest damage, condition of transport and housing infrastructure, access to clean water, health risks, etc.).

Most questions employed a numerical scale ranging from 1 to 10 to capture the subjective assessment of environmental conditions. While similar to a Likert-type scale, the expanded 10-point range increases the sensitivity and granularity of responses. Respondents independently selected a score reflecting their evaluation of each specific issue in their community.

To standardize interpretation, guidance was provided: a score of 1 indicated the absence of a problem or optimal condition (minimal negative impact), while a score of 10 denoted a critical state or severe issue. For example, in evaluating technogenic pollution, a score of 1 indicated no visible signs of contamination, whereas a 10 reflected extreme environmental burden involving multiple instances of air, water, or soil pollution. Similarly, for ecosystem condition, a score of 1 implied negligible damage, while 10 denoted complete destruction or irreversible loss of ecosystems and soil fertility. This approach enabled the generation of quantitative data on respondents' environmental perceptions, allowing for the calculation of relative indicators and comparison across communities.

In addition to the numerical scale, several dichotomous (yes/no) questions were included to establish the factual presence of certain conditions. For instance, questions on access to critical resources or exposure to specific threats (e.g., availability of drinking water or presence of landmine hazards) were binary in nature. These items were used to confirm the existence of issues, while subsequent scaled questions captured their severity. Accordingly, the survey combined metric scales (to measure intensity) with nominal variables (to register the occurrence of specific phenomena). All scales were pre-tested for clarity: several respondents completed a trial version of the questionnaire to ensure correct understanding of the 1–10 scale and other question formats.

Several limitations should be taken into account when interpreting the results and formulating recommendations. First, the representativeness of the sample is relative. Although 16,000 participants from 42 communities were surveyed, the sample was based on voluntary online participation. This introduces the potential for selection bias – those more active, with internet access and interest in the topic, may have been more likely to respond. Conversely, groups with limited internet access, such as elderly individuals or residents in remote villages, may be underrepresented. This limitation is common to online surveys and suggests that the results should not be directly generalized to the entire population without adjustments.

Second, all indicators are based on self-reported perceptions rather than objective instrumental measurements of environmental conditions. Thus, findings reflect respondents' subjective experiences, which may be influenced by their awareness, personal encounters, or emotional states following traumatic events. For instance, technogenic pollution may be underestimated in communities where the damage is not visually apparent, or overestimated in areas where anxiety levels are high. To mitigate this limitation, the questionnaire included specific follow-up items (e.g., whether respondents observed smoke, chemical odors, mass fish mortality, etc.). Nevertheless, subjective bias cannot be fully eliminated; therefore, the indicators should be interpreted as indices of public perception rather than precise physical metrics.

Third, due to security constraints, data collection was conducted remotely. This precluded controlled fieldwork, such as randomized household interviews in areas facing landmine threats or infrastructure destruction. Technical disruptions (e.g., power outages or unstable internet connections) may have further limited participation in some communities.

Moreover, the indicators derived from the survey do not account for temporal dynamics. The study employed a one-time data collection effort, capturing conditions at a single point in time. Given the dynamic nature of de-occupied areas – where demining, reconstruction, and seasonal environmental changes (e.g., floods or wildfires) are ongoing – longitudinal measurements are desirable. Repeated assessments would help identify trends, such as improvements resulting from interventions or the emergence of new challenges.

Despite these limitations, the findings provide a valuable data foundation. They address a critical gap in environmental data for de-occupied communities and can inform managerial decisions related to ecological restoration and infrastructure rebuilding. The combination of a large-scale sample and a clear methodology for calculating indicators ensures a sufficient level of reliability for community-level analysis.

Based on the collected data, five core environmental indicators were computed to reflect the environmental damage incurred by each community due to the full-scale invasion of Ukraine. These indicators were calculated by aggregating individual responses within each community and determining the proportion of respondents who reported significant problems in each thematic area. Each community-level indicator is expressed as a fractional value (ranging from 0 to 1.0), representing the perceived intensity of the issue. The formal formula used to calculate the indicator is provided below

$$I_{k,i} = \frac{n_{k,i}}{N_i},$$

where N_i – denotes the total number of respondents in community *i*, and $n_{k,i}$ – represents the number of respondents in the same community who reported a significant issue *k*. Depending on the question type, was defined as follows:

a) for items measured on a 1–10 scale: the number of respondents who selected values in the 8–10 range, which were interpreted as indicating a high intensity of the respective problem;

b) for dichotomous (yes/no) items: the number of respondents who answered "Yes", thereby confirming the presence of the problem.

Accordingly, the indicator reflects the proportion of surveyed residents in a given community who perceive a particular issue as severe.

Table 5.1 presents the computational logic underlying each of the five environmental sustainability indicators, capturing residents' perceptions of the environmental situation in their respective communities following de-occupation.

All indicators are measured on a scale from 0 to 1, where values closer to 1 indicate that the issue is more widely acknowledged and perceived as severe by residents of the respective community. These metrics allow for comparative analysis across communities and help identify territories that require priority interventions in specific environmental domains. They also serve as an empirical foundation for managerial decisions informed by adverse indicator outcomes.

Table 5.1 System of environmental sustainability indicators in de-occupied communities

Indicator Name		Definition	Formula
Techno-genic Pollution from Military Activity	TPMA	Proportion of community residents who reported significant environmental contamination due to military operations (e.g., chemical pollution, toxic remnants of munitions). A higher value (closer to 1) indicates that most respondents observed substantial pollution	$I_{\text{TPMA},\,i} = \frac{n_{\text{TPMA},\,i}}{N_i}$, where $n_{\text{TPMA},\,i}$ – the number of respondents in community i who rated the pollution level as high (8–10 out of 10) or confirmed the presence of such incidents
Degradation of Natural Ecosystems and Soil	DNES	Reflects the extent of ecosystem degradation (forests, meadows, protected areas) and loss of soil fertility as perceived by residents. A higher score indicates greater ecological damage as perceived by respondents	$I_{\text{DNES},\,i} = \frac{n_{\text{DNES},\,i}}{N_i}$, where $n_{\text{DNES},\,i}$ – the number of respondents who reported severe damage to ecosystems and soil, including signs such as burned or deforested areas, polluted land, or craters in agricultural fields
Infrastructure and Household War Impacts	IHWI	Share of respondents who reported serious infrastructure-related problems (housing, roads, water or electricity supply), or rated at least one key facility as critically damaged (8–10 on the scale)	$I_{\text{IHWI},\,i} = \frac{n_{\text{IHWI},\,i}}{N_i}$, where $n_{\text{IHWI},\,i}$ – the number of respondents in community i who reported severe infrastructure or household issues (e.g., rated infrastructure condition as 8–10 or selected critical issues from listed options)
Access to Natural Resources	ANR	Indicates the prevalence of problems related to access and safety of natural resources (e.g., drinking water, forests, farmland, water bodies). Higher values reflect widespread concerns about safety or shortages of resources	$I_{\text{ANR},\,i} = \frac{n_{\text{ANR},\,i}}{N_i}$, where $n_{\text{ANR},\,i}$ – the number of respondents who reported significant issues with resource access. This includes those who answered "Yes" to questions about safety concerns (e.g., mined forests or contaminated water bodies) or rated water availability/quality at a critical level
Biosecurity and Public Health Protection	BPHP	Proportion of respondents who expressed serious concerns about sanitation, epidemic risks, or access to healthcare. A higher value signals population-level concern about health-related threats	$I_{\text{BPHP},\,i} = \frac{n_{\text{BPHP},\,i}}{N_i}$, where $n_{\text{BPHP},\,i}$ – the number of respondents who rated biosecurity or health threats as severe (8–10), or reported serious concerns about related risks

Source: compiled by the authors based on [5, 10, 15, 16]

For instance, a community with a technogenic pollution index of 0.80 (80%) has a significantly higher proportion of residents reporting contamination compared to a community with an index of 0.20 (20%). This disparity underscores the need for urgent environmental remediation efforts in the former.

5.3 Theoretical foundations of sustainable development and environmental security in post-conflict recovery

The concept of sustainable development is based on the integration of three fundamental dimensions – environmental, social, and economic – with the goal of achieving balanced progress across all three spheres [6, 17]. In its classical formulation by the Brundtland Commission, sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [18]. In this sense, society must pursue economic growth and social progress without depleting natural resources or causing irreversible environmental harm. The emergence of this paradigm in the late 20th century was a response to the realization of the limitations inherent in the traditional, economically focused development model, which often neglected environmental and social consequences. By the early 1990s, the global community officially recognized sustainable development as the guiding ideology for human progress in the 21st century, which was reflected in numerous international agreements and initiatives.

Each of the three pillars of sustainable development has its own objectives and metrics. The environmental dimension focuses on preserving ecosystems and ensuring the rational use of natural resources. The social dimension addresses poverty reduction, access to quality education and healthcare, gender equality, and broader social justice [7, 8, 17]. The economic dimension emphasizes stable growth, innovation, sustainable industry, and infrastructure, while promoting efficient use of financial and material resources. Crucially, these three elements are treated holistically: sustainable development is conceived as a complex process of harmonizing social, economic, and environmental objectives to ensure effective use, protection, and regeneration of natural systems, alongside quality of life for both current and future generations [7, 8, 17]. The integrated approach assumes that progress in one area must not come at the expense of another. Consequently, sustainable development has become a global strategic policy direction, as evidenced by the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015 – a global framework encompassing all three dimensions of sustainability.

Indicator-based governance is a central tool in international practice for implementing the SDGs and guiding environmental policy. In 2015, the United Nations adopted 17 Sustainable Development Goals and 169 associated targets, which progress is tracked using a comprehensive system of quantitative indicators [1, 3, 17, 19]. To monitor implementation of the 2030 Agenda, an official global indicator framework was introduced, originally comprising 232 indicators covering a broad range of issues – from poverty, hunger, health, and education to environmental quality, climate change, and institutional capacity. Countries regularly collect and report data on these indicators within the UN framework, enabling both national performance assessment and international comparisons. Each SDG is linked to specific indicators with target thresholds to be achieved by 2030. For example, Goal 6 "Clean Water and Sanitation" includes indicators on access to safe drinking water and wastewater treatment, while Goal 13 "Climate Action" includes indicators on greenhouse gas emissions, climate adaptation policies, and climate finance. The entire SDG framework is based on the principle that "what gets measured gets managed", directing government efforts toward indicators falling short of targets.

The application of indicators is also well established at the national level. Many countries have adapted the global SDGs to their local contexts by setting national targets and indicators. Ukraine, for instance, has developed its own monitoring system, which includes 86 national targets and corresponding indicators, with defined benchmarks to be achieved by 2030 [12, 14, 17]. These indicators are integrated into national planning and statistical reporting systems, and their monitoring supports assessment of strategic implementation (e.g., the national report "Sustainable Development Goals: Ukraine" presents progress across key indicators) [17]. The Ukrainian government annually publishes updates on SDG performance and, in 2020, presented its first Voluntary National Review (VNR), which identified areas of strength and weakness and outlined priorities for future action [17, 20]. This international experience illustrates the utility of quantitative indicators in guiding development: they serve as the foundation for decision-making, policy adjustments, and resource allocation in underperforming areas.

Another example of an indicator-based approach is the European Green Deal – an ambitious political initiative launched by the European Union in late 2019, aimed at transforming the EU economy to achieve climate neutrality by 2050 [19]. The Green Deal encompasses a wide array of interconnected policy areas, including climate and energy, biodiversity, agriculture, transport, industry, and finance [10, 14, 19]. Progress in implementing this strategy is monitored using numerous indicators and benchmarks. The European Commission established a system to track key parameters (e.g., GHG emissions and their reduction relative to 1990 levels, share of renewables in the energy mix, energy efficiency, air and water quality indices, circular economy indicators, waste recycling rates, forest health, and ecosystem condition) [6, 19]. These data are used to assess progress toward both the intermediate targets for 2030 and the long-term goal for 2050.

In addition to official EU monitoring, independent research institutions and academics have also developed methodologies to assess the performance of the Green Deal. One such study proposed a rating system using a set of 26 key indicators from Eurostat, grouped into three thematic clusters [6, 19]. These indicators represent the core dimensions of the Green Deal: climate-energy (e.g., CO_2 emissions, share of renewables, energy efficiency); environmental (e.g., air and water quality, waste management, pollution, resource efficiency); and socio-economic (e.g., investment in green technologies, employment in the green sector, environmental innovation index). Based on the indicator values, composite scores were calculated to evaluate the degree of progress achieved by each EU member state. This approach allows for identification of strengths and weaknesses: some countries may lead in reducing emissions but lag in biodiversity conservation or waste management, while others exhibit the opposite pattern. By analyzing these gaps, the EU and national governments can recalibrate policies and intensify efforts in areas where targets are not being met. Overall, international experience underscores the central role of indicator systems in managing sustainable development. They ensure transparency, accountability, and evidence-based decision-making, promote best practices, and help coordinate the actions of different countries toward shared development goals.

Armed conflicts have devastating consequences not only for human lives and economic stability but also for the environment, creating unique challenges for post-conflict recovery from the perspective of environmental security. The war in Ukraine, launched by the Russian Federation in 2022, is a telling example: environmental damage has been estimated at over 56 billion USD, with widespread chemical pollution of air, water, and soil, and approximately 30% of the country's territory contaminated by mines and unexploded ordnance [20]. Around 30% of protected natural areas have suffered from military activities, including fires, explosions, and ecosystem destruction [20]. Certain war-related technogenic incidents have created long-term threats – for instance, the seizure of the Zaporizhzhia Nuclear Power Plant and the destruction of the Kakhovka Dam pose risks of regional-scale environmental catastrophe [20, 21]. Many of these impacts directly or indirectly endanger human health and safety, exacerbating the humanitarian crisis [14, 20]. Therefore, environmental considerations must be integrated into recovery planning. A just and lasting peace is impossible without restoring the natural environment alongside rebuilding damaged infrastructure.

One of the most complex issues in the post-conflict period is the management of vast amounts of debris and waste generated by destruction. In Ukraine, large-scale hostilities have produced unprecedented quantities of construction and mixed rubble – so-called "conflict-related waste". As of 2023, the destruction of thousands of buildings has resulted in millions of tons of debris (concrete, brick, metal, wood, glass, plastic, electronics), often including hazardous materials such as unexploded ordnance, explosives, toxic chemicals, asbestos, and e-waste [20, 22]. These wartime residues pose significant risks to both the environment and public health. Poorly managed waste threatens secondary contamination (e.g., soil poisoning by heavy metals, groundwater pollution), increases health hazards due to exposure to toxic substances, and can hinder reconstruction due to inaccessible or obstructed land [8, 22]. Unfortunately, Ukraine lacked a formal system for managing such waste at the onset of recovery; only in September 2022 was the first regulatory document on construction debris adopted [7, 22], and local communities still lack financial and technical capacity for safe collection, sorting, and processing [22]. This situation highlights the urgent need for specialized policy solutions and investment in environmentally sound waste management systems.

International post-conflict recovery experiences emphasize the critical importance of integrating environmental priorities into rebuilding efforts. Reports by the United Nations Environment Programme (UNEP) and joint studies by the World Bank, EU, and UNDP highlight the enormous volumes of debris in war-affected cities and stress the need to remove toxic and explosive residues to prevent long-term contamination [22]. Countries in the Middle East that have experienced major conflicts (e.g., Syria, Iraq, Lebanon, Gaza) have developed practices such as establishing temporary sites for rubble storage and sorting, deploying mobile recycling units, and coordinating between military and civil institutions to clear debris efficiently [7, 8, 22]. One of the core strategies has been the application of circular economy principles – maximizing reuse of materials, recycling concrete and metal as aggregate for construction, and repurposing suitable debris in road building. For Ukraine, these approaches are highly relevant: recycling construction waste and reusing materials can reduce pressure on landfills, conserve resources, and lower reconstruction costs. Moreover, international experts recommend involving local communities in waste management planning as early as possible, improving transparency and public access to environmental data on war-related damage [22]. Legal frameworks must also be updated: Ukrainian scholars advocate for defining "war waste" in legislation, streamlining environmental impact assessment procedures for demolition activities, and developing standards for safe dismantling and disposal [22].

In conclusion, post-conflict recovery requires an ecosystem-based approach with a strong emphasis on environmental security. Reconstruction must include: clearance of explosive remnants (demining of agricultural land and residential areas is critical for recovery and resettlement); remediation of technogenic disasters (monitoring water systems after dam explosions, restoring water supply, mitigating radiological risks); sustainable management of natural resources (avoiding overexploitation of forests and minerals); and modern waste management practices. Integrating environmental indicators into recovery planning can serve as a practical tool – for example, tracking water quality, soil conditions, and air pollution levels in de-occupied areas can help identify high-risk zones and prioritize intervention. All these measures align with the "build back better" principle – rebuilding infrastructure in ways that enhance sustainability and resilience. According to international law and expert consensus, lasting peace is impossible without ecological restoration. Ensuring environmental safety – through clean ecosystems, healthy landscapes, and minimized technogenic risks is essential for long-term recovery and population well-being.

5.4 Results of environmental indicator calculations and managerial implications for the sustainable recovery of post-conflict territories

Based on the responses collected through the survey, five environmental indicators were calculated, allowing for a quantitative assessment of the scale and nature of the war's environmental consequences in de-occupied communities in southern Ukraine. To ensure clarity and enable deeper analysis, the values of these indicators were visualized using a heat map.

The heat map provides a spatial overview of environmental stress across the studied communities, highlighting areas with critical values and indicating where the environmental impact of military actions is most extensive and multifaceted. This approach not only illustrates the current ecological condition of each community but also serves as a foundation for evidence-based decision-making in the context of recovery and sustainable development in post-conflict areas (**Fig. 5.1**).

In **Fig. 5.1**, the computed values for the five indicators – TPMA, DNES, IHWI, ANR, and BPHP – are displayed across 42 de-occupied communities in southern Ukraine. The indicator values vary widely. Most communities demonstrate moderate levels of environmental burden, with indicator scores falling within the mid-range (0.3 to 0.7 on a normalized 0–1 scale), represented in the map by orange tones. At the same time, a distinct group of communities exhibits elevated values across all five indicators (rows shaded in red tones on the heat map), signaling a high cumulative level of environmental stress at the community level.

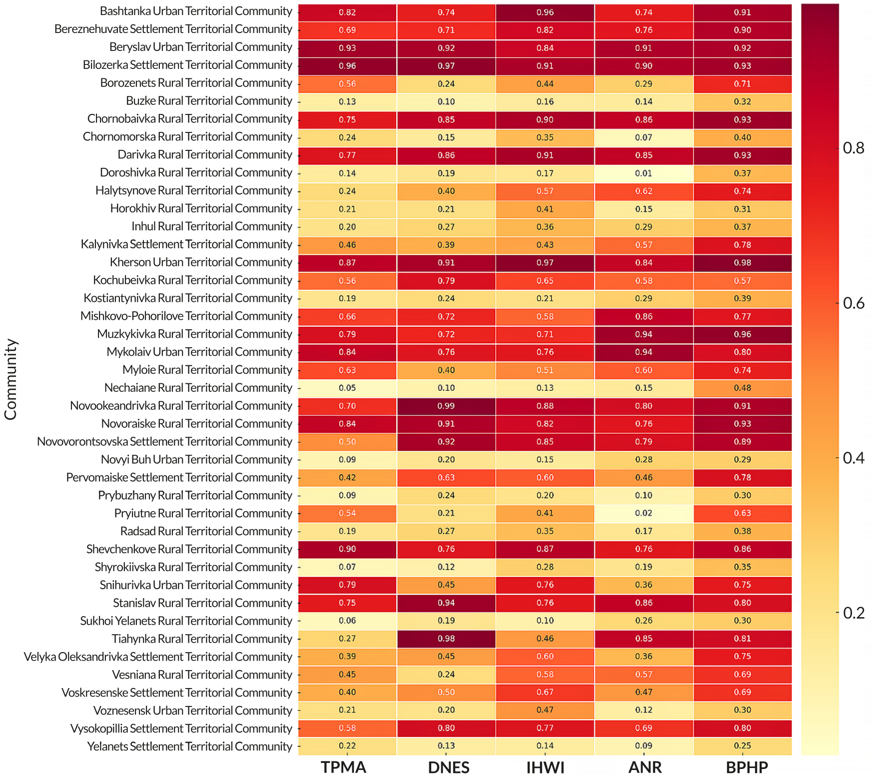

Fig. 5.1 Heat map of environmental indicators in de-occupied territorial communities of Southern Ukraine
Source: visualized by the authors

The highest aggregate scores across all environmental indicators were recorded in specific communities, particularly in Bilozerka Settlement Territorial Community and Kherson Urban Territorial Community. These communities are represented by the darkest red tones on the heat map, indicating values approaching the upper threshold (0.9–1.0). Such high scores reflect the extreme negative environmental impact of military operations in all evaluated domains – from technogenic pollution and ecosystem degradation to biosecurity challenges.

Also included in the group of most heavily burdened communities are Beryslav Urban and Dariivka Rural Territorial Communities, where the cumulative scores across the five indicators exceed 4.5 out of a possible 5. This highlights the presence of complex environmental challenges and identifies these locations as "hotspots" of ecological risk in de-occupied territories.

Conversely, several territorial communities are characterized by low levels of cumulative environmental stress, as indicated by consistently low values across all indicators (light yellow segments on the heat map). The lowest aggregate scores were observed in Yelanets Settlement, Buzke Rural, and Doroshivka Rural Territorial Communities, where the total indicator values are close to 0.8. In these areas, the indicators of technogenic pollution, ecosystem degradation, infrastructure condition, resource access, and biosecurity are among the lowest recorded across the entire sample. These results suggest a relatively limited environmental impact of hostilities and a faster ecological recovery in these communities compared to high-risk areas such as Bilozerka or Kherson.

To illustrate the relationship between the environmental conditions of de-occupied areas and corresponding managerial responses, a structural model of decision-making was developed. This model is based on the five environmental indicators and outlines the logical progression from problem identification to the implementation of sustainable recovery measures (**Fig. 5.2**).

Fig. 5.2 presents a stepwise structure encompassing:

– environmental indicators (TPMA, DNES, IHWI, BPHP, ANR);

– the typical problems identified through these indicators;

– strategic response proposals;

– specific actions for implementing these strategies;

– the anticipated outcomes of these interventions.

The model enables the integration of empirical analysis results into a framework for informed environmental governance, with a focus on local community needs and sustainable development principles. It not only synthesizes the findings of the study but also serves as a practice-oriented tool for local policy planning. Its application can help improve the effectiveness of decision-making, mitigate environmental risks, and strengthen community resilience for sustainable post-war development.

The implementation of managerial decisions aimed at addressing the environmental consequences of armed conflict requires more than just data and strategic vision – it also depends on well-defined funding sources. In the context of significant budget constraints, especially at the level of de-occupied communities, the mobilization of external resources, cross-sector partnerships, and innovative financing mechanisms becomes a pressing need.

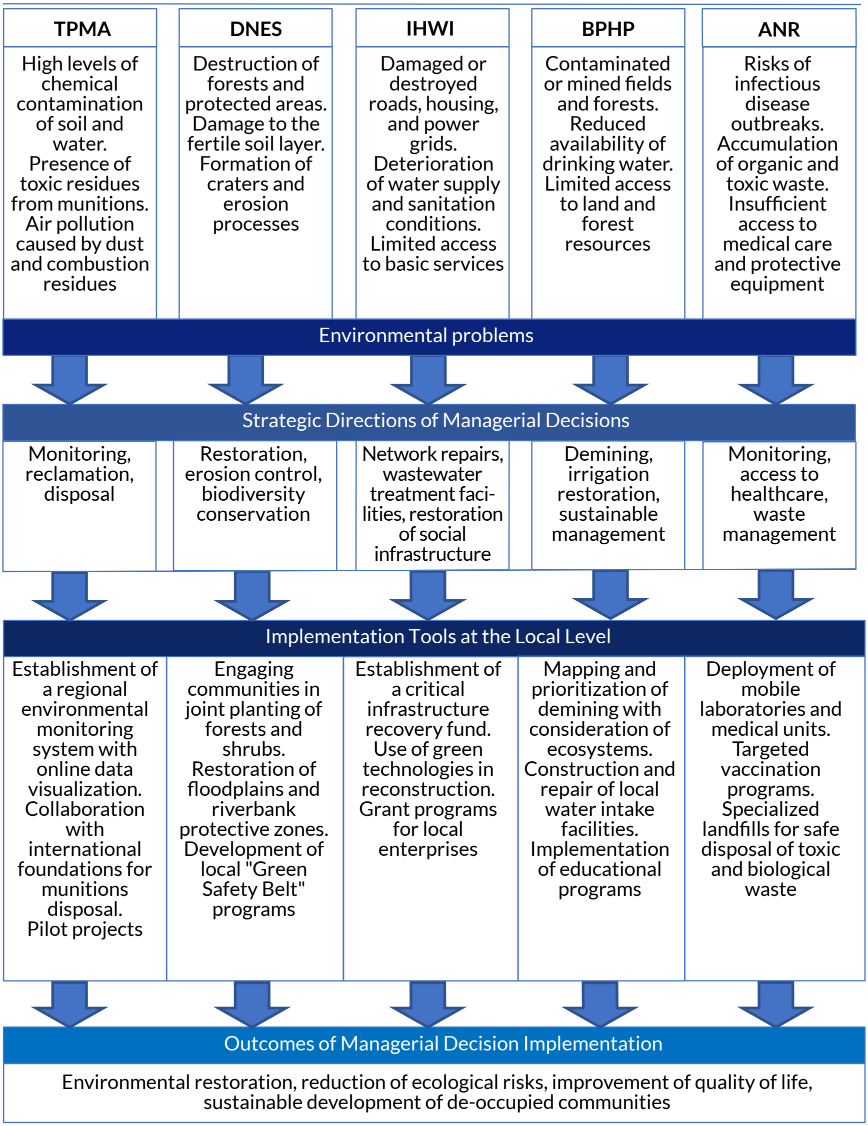

Fig. 5.2 Structural model of managerial decisions for sustainable recovery of de-occupied territories based on environmental indicators
Source: visualized by the authors

International donors play a pivotal role in financing environmental recovery efforts. The European Union, World Bank, UNDP, USAID, NEFCO, and other development partners are already supporting projects in Ukraine focused on demining, waste management, water infrastructure rehabilitation, and the deployment of energy-efficient technologies [23–26]. Several grant and investment programs are specifically tailored to assist war-affected communities, making the integration of environmental components into funding proposals a key factor in increasing their competitiveness and likelihood of approval.

Within Ukraine, both national and regional funds support environmental initiatives, including the State Fund for the Elimination of Consequences of Armed Aggression, the Environmental Protection Fund, and the Regional Development Fund. Through effective inter-municipal coordination, communities may submit joint projects – such as the construction of waste management facilities or the restoration of water resources – that address cross-cutting environmental challenges.

Equally important is the potential of public–private partnerships, particularly the engagement of the private sector in implementing eco-technologies and innovative solutions. Financial instruments such as green bonds, crowdfunding, and community-based investment in infrastructure and environmental protection projects offer additional avenues for mobilizing resources. In this context, it is essential that communities possess not only strategic planning documents, but also clear financial models that enable them to present their initiatives effectively to potential donors and investors.

Given the scale of environmental challenges and the limited availability of resources, the development of a coherent financing roadmap is a critical component of environmentally oriented recovery policy. Systematic planning, transparency, and openness to international cooperation significantly enhance the capacity of local governments and communities not only to address the consequences of war, but also to build long-term ecological resilience.

5.5 Conclusion

The findings of this study demonstrate that the sustainable recovery of Ukraine's de-occupied territories is not feasible without the systematic integration of environmental considerations into decision-making processes. The war has placed a substantial burden on the natural environment, manifested in increased technogenic pollution, ecosystem degradation, limited access to natural resources, compromised biosecurity, and the destruction of critical infrastructure.

Analysis of the sociological survey conducted across 42 de-occupied communities in southern Ukraine enabled the calculation of five core environmental indicators. These indicators not only reveal which territories are facing the most acute ecological challenges but also help identify priority areas for intervention. Visualization through a heat map and a structural decision-making model further underscores the practical value of the indicator-based approach in planning sustainable recovery efforts.

The proposed structural model for managerial decision-making provides a clear framework for transitioning from problem identification to the implementation of targeted strategic and operational actions. Its application at the community level can enhance transparency, legitimacy, and the overall effectiveness of environmental policy within the context of post-conflict reconstruction.

Moreover, the findings highlight the need to institutionalize environmental monitoring systems, foster civic science initiatives, establish open-access ecological data platforms, and promote inclusive decision-making involving local communities.

This study has several limitations, including reliance on self-reported assessments, a voluntary sampling methodology, and the absence of longitudinal data. Future research should aim to triangulate subjective perceptions with objective environmental measurements, conduct follow-up assessments to track dynamic changes, and expand the geographic scope to include other regions of Ukraine. A promising direction for future inquiry is the development of a national index of environmental resilience for post-conflict territories, integrating local-level data, SDG-aligned indicators, and policy performance evaluations. Additionally, regulatory improvements are urgently needed, particularly regarding the management of war-related waste and the environmental assessment of reconstruction projects.

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CHAPTER 6

Development of models and methods for assessing green skills in the labor market ecologization environment

Masuma Mammadova
Tetyana Baydyk
Zarifa Jabrayilova
Huseyn Gasimov
Turkan Alibeyli

Abstract

The modern world is faced with an unprecedented number of interconnected environmental problems, the key ones being environmental pollution, climate change, loss of biodiversity, depletion of natural resources. One of the most serious environmental problems of our time, affecting all aspects of life on Earth, is global climate change, caused mainly by anthropogenic factors. The negative impacts of the deepening climate crisis on the sustainable economic development of countries around the world have created a real threat to humanity in recent decades and have led the world community to recognize the need to transition to a green economy as a way to solve these problems. Green transformation, which involves the transition to sustainable and environmentally friendly technologies, leads to serious changes in the labor market, in particular, it causes changes in the sectoral structure of employment, rapid growth of green jobs in various sectors of human activity and, accordingly, the need for green skills necessary to use new technologies. The implementation of the green policy leads to the elimination of a number of professions and specializations and the emergence of new priority professions and specializations in the labor market, focused on the restoration of ecological systems and careful interaction of man with the environment. New professions and specializations requiring the acquisition of green skills generate a discrepancy between the demand for human resources of the required profile and their supply. This, in turn, actualizes the problem of effective selection of personnel with the necessary skills and determines the need to develop models and methods for assessing the supply and demand for specialists, providing an opportunity to assess the compliance of

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the proposed skills with the requirements of vacant green jobs. This chapter proposes a methodological approach to intelligent management of supply and demand in the green segment of the labor market. Fuzzy multi-criteria methods for supporting decision-making have been developed, allowing, in the context of green professions and specialties, to determine the degree of compliance of the proposed skills with the level of required green skills. Models and algorithms for supporting decision-making to identify the degree of "greenness" of the proposed skills to the requirements of green jobs are proposed, taking into account the multivariate nature of the coordination of supply and demand.

Keywords

Green jobs, green skills, intelligent management of supply and demand, greenness degree of the proposed skills.

6.1 Introduction

Ecological systems (ecosystems) are natural communities of living organisms (animals, microorganisms, plants, etc.) and the environment (air, water, soil, forests, climate, etc.), functioning together as a unit. Their state determines the well-being of the planet and man [1]. Ecological systems are quite vulnerable to anthropogenic impacts, and subject to pollution and depletion. The state of the ecosystem has a significant impact on the climate, biodiversity, and human health. A particularly serious environmental problem of modern time is climate change, which manifests itself through such indicators as global warming, rising (lowering) sea levels, water bodies, increased frequency and intensity of extreme weather events such as droughts, floods, hurricanes, forest fires, and other emergencies.

In recent decades, humanity has particularly felt that the uncontrolled production and use of traditional energy, emissions of which account for 75% of all greenhouse gases polluting the atmosphere, are leading the world to a catastrophe. Not by coincidence the issues of reducing the global climate change and the environmental problems, developing a "green economy" and clean energy, providing each inhabitant of the planet with the access to clean energy were the discussion topics at the annual general debate of the 76th Session of the UN General Assembly with the participation of leaders of states and governments of 193 member-countries, September 21–27, 2021, New York. Countries specific commitments were made to reduce the hydrocarbon share and "decarbonization" of energy industry in the following ten years in order to implement the Paris Climate Agreement, which is a legal international treaty on climate change [2].

To date, all UN member countries have ratified the Paris Agreement, which sets the goal of preventing global temperatures from rising by more than 2°C. Each country has committed to Nationally Determined Contributions (NDCs) to reduce greenhouse gas emissions. In this regard, the ever-growing demand for energy in the world is accelerating the gradual transition of nation-states to green energy. The implementation of NDCs includes commitments to reduce greenhouse gases in the energy, agriculture, transport, and other sectors.

However, national commitments and sectoral priorities for implementing the Paris Agreement tend to underestimate the role of skills development. The key role of human capital in preventing environmental disaster is often overlooked when developing policies and plans to support the transition to a green economy. This increases the skills shortage and impairs the skills mismatch in the emerging green segment of labor market. Therefore, most companies face difficulties in recruiting professionals with the necessary green skills for the available green vacancies.

According to a study by Cedefop (European Centre for the Development of Vocational Training), professions requiring a transition to green skills accounted for around 40% of the total number of online job advertisements in the EU between 2020 and 2022 [3]. The European Commission estimates that an additional 884,000 jobs could be created in the EU by 2030 with the climate goals of the European Green Deal [4]. This estimate takes into account job losses in sectors such as coal mining or polluting industries and job growth in areas such as renewable energy, agriculture, the circular economy [5, 6]. At the same time, sectors such as transportation and storage, water supply, agriculture, renewable energies, energy storage and waste management, which are critical to the transition to a green economy, are experiencing labor shortages [4].

An analysis of data on developing and transition countries conducted by the International Renewable Energy Agency (IRENA) found out that the renewable energy sector alone would employ 13.7 million people in 2022, compared to 7.3 million in 2012. IRENA estimates that the large investments required to meet climate objectives could create many millions of additional jobs in the coming decades [7].

LinkedIn data, covering 48 countries and 930 million users worldwide, also shows that the demand for green jobs is growing almost twice as fast as the availability of workers with the necessary skills to fill these vacancies. In 2023, 7.3% of job postings on LinkedIn were for a green job or required green skills, in 2024, that figure rose to 7.7% [8].

According to the International Labor Organization (ILO) estimations, if countries take measures to achieve the goals set in the Paris Agreement, about 24 million green jobs will be created worldwide by 2030, with the majority of them in Asian countries. Moreover, approximately 6 million jobs are estimated to be closed. Taking into account the losses, the net increase in jobs will be 18 million [9].

As follows from the statistics above, the problem of increasing demand for human resources with skills supporting the green transition is quite relevant for all regions and countries all over the world. Growing demand for new green skills requires adaptation to new environmental requirements, changing the thinking and lifestyle of each person to make informed decisions to reduce negative impacts on the environment and improve the environmental situation [10, 11].

The process of ecosystem recovery promotes the emergence of new areas of employment, the creation of green jobs, makes the problem of effective selection of personnel with green skills relevant and determines the need to develop models and methods for assessing green skills and green jobs.

6.2 Related work

Successful implementation of net zero policies requires measures to eliminate the mismatch between supply and demand for skills in the green segment of the labor market. In this context, it is first necessary to clarify what the terms "green jobs" and "green skills" mean. Further, taking into account the content of these two conceptual concepts, it is possible to review the main areas of research devoted to identifying the relationship between the green transition and the corresponding skills.

The literature review shows that today specialized international organizations and research institutes have adopted various definitions and methodological approaches to analyze and identify green jobs and green skills. However, the lack of a single generally accepted definition and the heterogeneity of methodological frameworks lead to significant differences in the results of studies, especially when trying to quantify green jobs and determine the necessary green skills. Moreover, a number of green skill indicators are assessed only by qualitative characteristics that cannot be described using traditional methods. Therefore, the degree of "greenness" attributed to various profiles of professions and positions can vary significantly depending on the field of activity. The adoption of a unified definition is even more difficult at the international level, since each country has its own specific political and economic context, intellectual potential and methodological approach to defining these concepts. Currently, very few countries have monitored and assessed the green skills market. Taking these factors into account, the authors of this paper refer to definitions proposed by leading international organizations.

According to the ILO definition, "green jobs are decent jobs that contribute to preserve or restore the environment, be they in traditional sectors (manufacturing, construction etc.) and in new, emerging green sectors (renewable energy, energy efficiency)". They are divided into two categories [12]:

1) jobs that design and produce goods or provide services that benefit the environment, such as green buildings, clean transportation and renewable energy, sustainable food;

2) jobs that contribute to more environmentally friendly processes in the production of any product or service, e.g. increasing water or energy efficiency, improving recycling systems etc.

In accordance with the US Green Economy Program, initiated in 2009, the online Occupational Information Network O*NET developed a methodology for data collection based on the use of scientific journals, commissioned reports, industry white papers, and government technical reports on green and non-green issues and identified approximately 100 professions included in the green economy. To identify green economic sectors, green occupations, and green tasks, their potential to reduce harmful impacts on the environment (e.g., by the reduction of the use of fossil fuels, the decreasing pollution and greenhouse gas emission, the developing renewable sources of energy) was taken into account. Using this definition, the experts classify occupations into three general categories, which are also included in the O*NET taxonomy [13]:

1) existing occupations that are expected to be in high demand due to the Green Increased Demand;

2) occupations the task content of which will undergo significant changes due to the greening of the economy (Green-Enhanced Skills);

3) New & Emerging Green. Currently, the number of occupations included in the green category by O*NET is 204.

In the European Union, the definition of green skills proposed by Cedefop is used to identify green jobs, occupations and skills. According to this definition, green skills are understood as "knowledge, abilities, values and attitudes needed to live, work and act in economies and societies seeking to reduce the impact of human activity on the environment" [14].

The systematization of knowledge and skills related to the green transition in the EU is carried out within the framework of ESCO (European Skills, Competences, Qualifications and Occupations) and is based on the definition of green skills proposed by Cedefop. ESCO works as a dictionary, describing, identifying and classifying professional occupations and skills relevant for the EU labor market and education and training [15], and includes the identified green skills and green jobs in its taxonomy. The taxonomy also defines which skills and knowledge concepts are essential or optional for a particular occupation's green economy and identifies green transition skills that can be applied across different occupations.

The identification of green professions and skills was performed through a group expert assessment of the skill requirements specified in vacancies and the processing of online vacancies using machine learning algorithms. The resulting ESCO skills base was divided into three groups [16, 17]:

1) brown skills, which are defined as knowledge and skills that increase the impact of human activity on the environment;

2) white skills, which do not increase nor reduce the impact of human activity on the environment;

3) green skills, which reduce the impact of human activity on the environment.

Currently, the ESCO taxonomy contains 381 green skills, 185 knowledge concepts and 5 transversal skills.

Skills for the green economy consist of:

– **specific skills**, required to adapt or implement standards, processes and services to protect ecosystems and biodiversity, and to reduce energy, materials and water consumption;

– **transversal skills** (digital, interdisciplinary, entrepreneurial, sustainable management, communication and negotiation skills**)**, linked to sustainable thinking and acting, relevant to all economic sectors and occupations;

– **highly specialized skills**, required to develop and implement green technologies such as renewable energies, sewage treatment or recycling. Skills for the green economy are also referred to as skills for green jobs, skills for the green transition or green skills.

According to [18], the transition to a green economy will lead to a reduction in jobs in sectors with high levels of emissions and environmental pollution, while new green jobs will be created in cleaner industries and will cause large changes in the demand for green professional skills.

In the study [19], the authors came to the following conclusion:

a) the rate of implementation of green technologies in various sectors of the economy and their impact on skill requirements are difficult to quantify;

b) the level of changes in the demand for professional skills depend on the specific characteristics of individual sectors.

In [20, 21], the authors estimate the lack of skills in green sectors as a vulnerable factor holding back the implementation of innovations and technologies.

The studies [22–24] estimate the share of US jobs that would benefit from the transition to a green economy using the online database O*NET and its definition of green jobs.

An analysis of green jobs has revealed differences in the degree of greenness. This suggests that the term greenness should be considered as a continuum rather than a binary characteristic. Greenness measures for four general green skill categories (engineering and technical science, operation management and monitoring) are proposed [22, 24].

In order to draw policy stakeholders' attention to the breadth of green skills needed to achieve climate justice, the authors propose a skills framework for the green economy [25]. They show the conceptualization of green skills through a gender and adolescent lens in the greening, sustainable development and education areas.

In the discussion paper [26], given that the green transition is set to accelerate over the next decade and trigger structural changes in EU labor markets, it is provided descriptive data on regions and demographic groups expected to be most affected by shifts between sectors, firms and occupations, and discusses the policy implications.

In [27] the results of observation of development of green jobs in Scotland are obtained using a hybrid approach. The authors conclude that the most important is not the total number of jobs, but the types of green jobs created and the spread of their impact on the economy.

A. Sulich, L. J. Kozar analyze Green Competences within Green Human Resource Management on the basis of the literature review [28]. The authors give various definitions of green competencies and examines their connection with the context of the problem being solved.

A review of the literature on the analysis of the impact of skills on the green transition has yielded several conclusions:

1. One of the obstacles to assessing the impact of the green transition on demand (green jobs) is the difficulty of identifying the skills needed for the green transition.

2. Research related to the transition to a green economy mainly focuses on identifying green occupations (jobs), skills and employment forecasts.

3. The ad hoc studies of occupations and skills conducted to date, due to their small number and methodological differences, do not complement each other and therefore cannot provide an up-to-date picture of the changing demand for skills.

4. The most valuable information on green jobs and green skills is collected at the sectoral level, which makes it possible to set targets for each individual industry.

5. Research and policy initiatives rarely take into account the human resources needed to support the green transition. This increases uncertainty in assessing the supply and demand for the relevant skills.

6. The pace of green technology adoption across sectors and its impact on human resource requirements with green skills are difficult to assess quantitatively and qualitatively.

7. Methods for assessing the match of skills offered to green workplace need to be developed to select workers with the required green skills.

6.3 Objective and general statement of the problem

Taking into account the findings, let's accept the existence of designated green occupations and skill sets across various sectors of the economy. The aim of the present study is to determine the compatibility of the set of skills offered by the applicant with the set of green skills characterizing green jobs (vacancies) in the recruitment process for green jobs and to evaluate the degree of "greenness" of the applicant's skills.

The conducted review and listed conclusions identify the problem of management of the green demand and green supply in the green labor market as semi-structured and difficultly formalized tasks [29, 30]. Obviously, for the solution of such problems, the use of intelligent methods and technologies based on fuzzy logic, is most effective. In this interpretation, solution of the management problem labor market assumes:

– selection of the most demanded green professional groups and specialties on the labor market;

– identification of requirements for green professional and personal competencies of specialists demanded on the labor market most in the context of each professional group or specialty;

– development of situational models of supply and demand in ever-changing labor market;

– comparison and evaluation of fuzzy situation of supply and demand in the current situation;

– deciding on the choice of a policy for their compliance.

The labor market can be referred to socio-economic ("soft") systems for its properties. This market is a social system as its key resources include people, intellectual potential, personal and psychophysiological qualities, the preferences of the latter, without which the management of the social system will be ineffective [30]. The success of a specialist in performing professional duties depends on his/her intellectual potential, the degree of certain professional and personal competencies, the willingness to adequately apply them at a particular workplace, the desire and ability to improve and regularly update his/her knowledge and experience in the professional field in accordance with the functional requirements to the latter. In this context, the approach to the labor market as an intellectual environment seems promising, in which knowledge, skills and abilities act as a commodity [31], for the formalization of which the theory of fuzzy sets is used [32].

As follows from the above, in order to assess and identify the degree of consistency between supply and demand in the context of various professional groups and specialties, it is necessary to solve two problems:

Problem 1 – identifying supply and demand for green professional groups and specialties needed in the labor market.

Problem 2 – identifying supply and demand for professional skills, specific to certain green specialty, and personal competencies for specialists in the context of each professional group or specialty, considered from the standpoint of individual subjects of the labor market (specialists and employers) and their behavioral strategies.

6.3.1 Problem statement 1

It is possible to assume that there are a predetermined number of green professional groups and specialties identified by examining the structure of the labor market [33]. It is required to assess the need for professional groups and specialties, their ranking (streamlining) from the most promising to low demand from the positions of demand in the green segment of labor market. It is possible to note that the ordering of the list of professional groups and specialties takes into account the demand for a particular green specialty as a whole, and not as the probability of employment of each specialist or graduate.

Problem solution 1.

Variant A. The method for fuzzy multicriteria individual expert decisions on the choice of priority professional groups and specialties.

Let's consider the method for selecting and arranging the alternatives of professional groups (or specialties) in the case when the criteria assessments of one expert are set as the degree of satisfaction of alternatives characterizing them (criteria, properties). The decision-making process in this case is reduced to a rational choice of alternatives, taking into account a set of features and preferences of an individual expert or decision maker, who are the same person here.

Let $X = \{x_1, x_2, ..., x_n\} = \{x_i, i=\overline{1,n}\}$ be a set of alternatives, which are the list of green specialties to be considered. $K = \{k_1, k_2, ..., k_m\} = \{k_j, j=\overline{1,m}\}$ denotes a set of criteria (features, properties) characterizing the alternatives. It is necessary to choose the best alternatives (green specialties) out of the evaluated ones, i.e., the most required specialties in the labor market from the standpoint (preferences) of an expert.

In this case, a specific alternative (green professional group or green specialties), on the one hand, is characterized by the relation of the criteria with the specified alternative, i.e., by the assessment of the green alternative for all criteria, on the other hand, by the relation of preference with this alternative for each of the criteria. This means that a fuzzy set can be defined for m criteria $K = \{k_1, k_2, \ldots, k_m\} = \{k_j, j = \overline{1,m}\}$ chosen for the assessment of the green alternatives.

$K = \{\mu_k(x_1)/x_1, \mu_k(x_2)/x_2, \ldots, \mu_k(x_n)/x_n\}$, where the membership function $\mu_k(x_i) \in [0,1]$ is the assessment of the alternative x_i for the criterion K, which characterizes the degree of satisfaction of the alternative x_i with the concept determined by the green criterion K.

The degree of satisfaction of the set of alternatives X with the green criteria $K = \{k_j, j = \overline{1,m}\}$ is determined by the set of membership functions $\mu_{k_j}(x_i): X \times K \to [0,1]$, $j = \overline{1,m}$, where $\mu_{k_j}(x_i)$ expresses the degree of satisfaction of the alternative x_i to the green criterion k_j. The best alternative, in this case, is that which satisfies all green criterion, i.e., both k_1 and $k_2, \ldots, k_m$, i.e. $\Omega = k_1 \cap k_2 \cap \ldots \cap k_m$.

Then the rule for choosing the best (non-dominated) alternative can be written as the intersection of the corresponding fuzzy sets and reduced to a multicriteria problem of fuzzy mathematical programming, for the solution of which the generalized Bellman-Zadeh approach is applied [33, 34].

Variant B. The method for fuzzy multi-criteria group decision on the choice of the most priority green professional groups and specialties.

Let $X = \{x_1, x_2, \ldots, x_n\} = \{x_i, i = \overline{1,n}\}$ be a set of alternatives, out of which it is necessary to choose the best one by the degree of greenness. $K = \{k_1, k_2, \ldots, k_m\} = \{k_j, j = \overline{1,m}\}$ is a set of criteria, features or indicators characterizing the greenness of alternatives.

The set of acceptable alternatives is represented by a two-dimensional matrix, in which the degree of satisfaction of the alternative x_i with the green criterion k_j is determined by the membership function $\varphi_{k_j}(x_i): X \times K \to [0, 1]$.

Set of experts G is formed by the decision maker (company manager), who is guided by his/her own opinion on the level of their competence in the field of greenness assessment. For each of the experts $g \in G$, a fuzzy preference relation is defined on the set of alternatives X, i.e., the membership function of the form $\psi: X \times X \times G \to [0,1]$. Certainly, in the process of multi-criteria assessment of alternatives, experts proceed from their own preference relations. The value $\psi(x_i, x_j, g)$

is interpreted as the degree of preference of the alternative x_j to the alternative x_i, through the prism of the preferences of the expert g and is determined as follows

$$\psi(x_i,x_j,g)=\begin{cases}1-\left[\varphi(x_j,g)-\varphi(x_i,g)\right], & \text{if } \varphi(x_j,g)\geq\varphi(x_i,g),\\ 1, & \text{if } \varphi(x_j,g)\leq\varphi(x_i,g),\end{cases} \qquad (6.1)$$

where $\varphi(x_i, g) = \min\{\varphi_{k_j}(x_i,g), j=\overline{1,m}\}$.

Using the expression (6.1) of each expert, a matrix of fuzzy green preference relations of alternatives is determined.

On the other hand, the decision maker (DM) unequally evaluates the competence of experts invited by them to assess alternatives. This factor is represented by the coefficient of competence of experts: $\gamma(g) \to [0,1]$, taking into account the expression

$$v(g_1,g_2)=\begin{cases}1-\left[\gamma(g_2)-\gamma(g_1)\right], & \text{if } \gamma(g_2)\geq\gamma(g_1),\\ 1, & \text{if } \gamma(g_2)\leq\gamma(g_1),\end{cases} \qquad (6.2)$$

from which v: $G \times G \to [0,1]$ is determined – fuzzy relation of expert competence. The value $v(g_1, g_2)$ is understood as the degree to which, in the opinion of the DM, the expert g_1 is more competent than the expert g_2.

Afterwards, the problem is reduced to a rational choice of alternatives from the set X, taking into account the information described above. According to [35] $\psi^{n.d.}(x_i, g)$ defined as a fuzzy subset of non-dominated alternatives, corresponding to a fuzzy preference relation $\psi(x_i, x_j, g)$ with fixed $g \in G$

$$\psi^{n.d.}(x_i,g)=1-\sup_{x_j\in X}\left[\psi(x_j,x_i,g)-\psi(x_i,x_j,g)\right]. \qquad (6.3)$$

The alternatives that give the largest possible value of the membership function $\psi^{n.d.}(x_i, g)$ on the set X coincide with the individual solution of the g-th expert.

Further, the fuzzy relation $v(g_1, g_2)$ is generalized to the class of fuzzy subsets of the set G. The induced (generalized) fuzzy relation on the set X is defined as follows

$$\eta(x_i,x_j)=\sup_{g_1,\,g_2\in G}\min\left\{\psi^{n.d.}(x_i,g_1),\psi^{n.d.}(x_j,g_2),v(g_1,g_2)\right\}. \qquad (6.4)$$

This fuzzy preference relation is the result of a "convolution" of a family of fuzzy relations $\psi(x_i, x_j, g)$ into a single resulting fuzzy preference relation, taking into account information about the competence of experts in a given subject area.

Induced preference relations on the set X make it possible to proceed to the problem of choosing alternatives with a single preference relation by defining the corresponding set of non-dominated alternatives

$$\tilde{\eta}^{n.d.}(x_i)=1-\sup_{x_j\in X}\left[\eta(x_j,x_i)-\eta(x_i,x_j)\right]. \tag{6.5}$$

Finally, from the expression

$$\eta^{n.d.}(x_i)=\min\left\{\tilde{\eta}^{n.d.}(x_i),\eta(x_i,x_j)\right\} \tag{6.6}$$

the corrected fuzzy set of non-dominated alternatives is determined and an alternative is chosen that delivers the maximum of the $\eta^{n.d.}(x)$ function

$$\eta^{n.d.}(x)=\sup_{x_j\in X}\eta(x_i), \tag{6.7}$$

which is the most effective alternative. The selected alternative is the resulting group choice decision and coincides with one of the individual decisions.

Based on the approach proposed in [33], an empirical experiment is described for obtaining a regulated list of specialties for the ICT professional group and determining the most priority specialties.

6.3.2 Problem statement 2

In accordance with the concept of intelligent supply and demand management [30, 31], the labor market is viewed as an intellectual space in which its main subjects interact. These subjects represent the demand (employers) and supply (specialists in various fields).

In the context of green transition, green skills/competencies of specialists that integrate the personified intellectual potential of the latter, expressed by a set of professional (green) and personal competencies, are considered as a product in the labor market.

It is required to develop the tools for managing the coordination of supply and demand in the context of various professional groups, individual professions and specialties that are in demand in the green segment of the labor market most. Moreover, an effective balancing involves the development of approaches, models and methods for assessing supply and demand of skills in the green segment of the labor market and making the best management decisions (strategies and measures) to minimize the imbalance between supply and demand for green skills in various labor sections (according to the hierarchy in management, vocational qualification, competence, quantity, quality, etc.).

It is possible to assume that the demand in the labor market is defined by the set:

– $V=\{V_i\}, i=\overline{1,k}$, expressed in terms of the number of vacancies;

– $L=\{l_j\}, j=\overline{1,n}$ – a set of personal features (characteristics) required from a candidate to a particular green position (job, workplace);

– $C=\{c_f\}, f=\overline{1,m}$ – a set of green skills/competencies, which a candidate must have for a vacancy (specific or super-specific for a profession, transversal (universal), i.e., necessary for all professions);

– $U=\{u_\gamma\}, \gamma=\overline{1,p}$ – a set of conditions offered to the applicants to green vacant jobs.

The demand model $V=(L, C, U)$ can be described by three matrices $V_L=\|l_{ij}\|_{k,n}$, $V_C=\|c_{if}\|_{k,m}$ and $V_U=\|u_{i\gamma}\|_{k,p}$, where each $i=\overline{1,k}$ of the row (V_i) characterizes individual green vacancy in the green segment of the labor market; columns:

– l_j, where $j=\overline{1,n}$ displays a constantly expanding base of personal features, allowing to keep systematically developing green skills up to date;

– c_f, where $f=\overline{1,m}$ – a set of green skills/competencies that characterize the employer's skill requirements for a green workplace;

– u_γ, where $\gamma=\overline{1,p}$ conditions offered to the applicants to a specific green vacant job.

The matrix elements V_L (i.e., l_{ij}, where $i=\overline{1,k}$, $j=\overline{1,n}$), V_C (i.e., c_{if}, where $i=\overline{1,k}$, $f=\overline{1,m}$) and V_U (i.e., $u_{i\gamma}$, where $i=\overline{1,k}$, $\gamma=\overline{1,p}$) express the employer's requirements for the level of indicators l_j, c_f, $u_{i\gamma}$ characterizing the offered green vacancy V_i. Requirements for the level of possessing green skills by the applicants are described in the form of linguistic variables and their values. The latter correspond to verbal rating scales representing the intensity of the possession of greenness of indicators (for example, extremely high, high, medium, satisfactory, low) [32–36].

Accordingly, the degree of conformity of the vacancy V_i by the indicators l_{ij}, c_{if} and u_{kp} is defined as fuzzy sets with membership functions

$$\mu_{l_j}(V_i): V\times L\to[0,1],\ \mu_{c_f}(V_i): V\times C\to[0,1],\ \mu_{u_\gamma}(V_i): V\times U\to\left[0,1\right]. \quad (6.8)$$

It is possible to assume that the supply in the labor market is given as set of specialists $S=\{S_g\}, g=\overline{1,q}$ looking for work and applying to a particular green vacancy; $L=\{l_j\}, j=\overline{1,n}$ – a set of actual competencies characterizing the specialists; $C=\{c_f\}, f=\overline{1,m}$ – a set of actual competencies of each individual applicant to a green vacancy; $U=\{u_\gamma\}, \gamma=\overline{1,p}$ – a set of preferences of the specialist expressed as his/her requirements for the green vacancy.

The supply model $S = (L, C, U)$ is also given as three matrices: $S_L = \|l_{gj}\|_{q,n}$, $S_C = \|c_{gf}\|_{q,m}$ and $S_U = \|u_{g\gamma}\|_{q,p}$, where each row (S_g) $(g = \overline{1,q})$ characterizes individual candidates to proposed green vacancies in the job market; columns l_j, c_f, u_γ $(j = \overline{1,n}, f = \overline{1,m}, \gamma = \overline{1,p})$ represent the constantly expanding base of personal features, competencies and requirements of the specialist for a green vacancy.

The matrix elements S_L (i.e., l_{gj}, where $g = \overline{1,q}$, $j = \overline{1,n}$), S_C (i.e., c_{gf}, where $g = \overline{1,q}$, $f = \overline{1,m}$) and S_U (i.e., $u_{g\gamma}$, where $g = \overline{1,q}$, $\gamma = \overline{1,p}$) represent the level of a specialist's possession of individual green features that are specified by linguistic variables and their values.

The degree of compliance of a certain specialist S_g, $g = \overline{1,q}$ to the criteria l_j, c_f and u_γ is defined by the membership function

$$\mu_{l_{gj}}(S_g): S \times L \to [0,1],\ \mu_{c_{gf}}(S_g): S \times C \to [0,1],\ \mu_{u_{g\gamma}}(S_g): S \times U \to [0,1].$$

In fact, there are two sets of fuzzy situations describing the conditions of demand for green skills $\tilde{V}_i$ and supply $\tilde{S}_g$ in the green segment of the labor market:

$$\tilde{V}_i = \left\{ \left\langle \mu_{l_{gj}}(V_i) \right\rangle, \left\langle \mu_{c_{gr}}(V_i) \right\rangle, \left\langle \mu_{u_{gz}}(V_i) \right\rangle \right\} = \left\{ \mu_{V_i}(y)/y \right\}, \tag{6.9}$$

$$\tilde{S}_g = \left\{ \left\langle \mu_{l_{gj}}(S_g) \right\rangle, \left\langle \mu_{c_{gr}}(S_g) \right\rangle, \left\langle \mu_{u_{gz}}(S_g) \right\rangle \right\} = \left\{ \mu_{S_g}(y)/y \right\}. \tag{6.10}$$

Here, set $\tilde{V}_i = \{\mu_{V_i}(y)/y\}$, $i = \overline{1,k}$ represents fuzzy reference green situation, and set $\tilde{S}_q = \{\mu_{S_q}(y)/y\}$, $g = \overline{1,q}$ represents fuzzy real green situation.

Problem solution 2.

Multi-scenario approach to decisions on the correspondence of supply and green demand, i.e., offered skills for the specialists in the context of each individual professional group or specialty.

The procedure of fuzzy similarity situations is used to correspond the supply and demand for the identified priority professions or specialties. The procedure of pattern recognition involves the following steps:

– real situations are determined (search patterns of specialists) in accordance with the green indicator's values that characterize each applicant for the announced green vacancy (supply), real situations are determined (search patterns of specialists);

– reference situations are determined (search patterns of requests) in accordance with the green indicators' values that characterize the employer's requirements to the applicant for the vacancy (demand);

– degree of green similarity of the reference situation to each real situation is calculated in accordance with the chosen measure of assessment of similarity between two fuzzy situations;

– real situation is revealed, which has the greatest green proximity rate with the reference situation. In other words, a decision is made on the green correspondence of supply and demand to the requirements of the employer (decision-maker (DM)).

The work [37] reviews various measures to determine the proximity rate between two fuzzy situations, involving single-stage or multistage measurement procedures. The case study uses the degree fuzzy inclusion of a situation $\tilde{S}_g$ in a fuzzy situation $\tilde{V}_i$, and the degree of fuzzy equality of $\tilde{S}_g$ and $\tilde{V}_i$ as the measure of identifying the proximity rate of demand (fuzzy reference situations) and supply (fuzzy real situations).

The degree of fuzzy inclusion of a fuzzy situation $\tilde{S}_g$ in a situation $\tilde{V}_i$ is determined based on the following formula

$$\mu(\tilde{S}_g,\tilde{V}_i)=\&\mu(\mu_{S_g}(y),\mu_{V_i}(y))=\underset{y\in Y}{\&}(\max(1-\mu_{S_g}(y),\mu_{V_i}(y)))= \\ =\min(\max(1-\mu_{S_g}(y),\mu_{V_i}(y))). \tag{6.11}$$

The situation $\tilde{S}_g$ is considered fuzzy inclusive in the situation $\tilde{V}_i$ ($\tilde{S}_g \subseteq \tilde{V}_i$), if the degree of inclusion of $\tilde{S}_g$ in a situation $\tilde{V}_i$ is not less than the inclusion threshold ($\psi \in$ [0.6, 1] determined by the management conditions), i.e. $\mu(\tilde{S}_g,\tilde{V}_i)\geq\psi$.

The degree of fuzzy equality $\tilde{V}_i$ and $\tilde{S}_g$ is defined by the following formula

$$\mu(\tilde{S}_g,\tilde{V}_i)=\vee(\tilde{S}_g,\tilde{V}_i)\&\vee(\tilde{V}_i,\tilde{S}_g)=\&\mu(\mu_{S_g}(y),\mu_{V_i}(y)= \\ =\min_{y\in Y}\left[\min(\max(1-\mu_{S_g}(y),\mu_{V_i}(y)),\max(1-\mu_{V_i}(y),\mu_{S_g}(y)))\right]. \tag{6.12}$$

Situations $\tilde{S}_g$ and $\tilde{V}_i$ are considered to be fuzzy equal $\tilde{S}_g \approx \tilde{V}_i$, if $\mu(\tilde{S}_g,\tilde{V}_i)\geq\psi$, $\psi\in\left[0.7,1\right]$, where ψ is a certain threshold of fuzzy equality of situations.

After the completion of the process of recognizing the most acceptable green similarity of the pair of "fuzzy reference pattern – fuzzy real pattern" in terms of proximity rate, there may be several possible scenarios among the sets of real search patterns of specialists (supply) and reference green search patterns of the query (demand) [30, 31]:

Scenario 1. One vacancy (employer's request) – one applicant (specialist), i.e., "one fuzzy reference pattern – one fuzzy real pattern".

In this case, if the degree of fuzzy similarity of the two situations (i.e., $\tilde{S}_g$ and $\tilde{V}_i$) is not less than the threshold accepted by the employer (for example, $\psi \in$ [0.6, 1]), then a hiring decision is made.

A flowchart of the decision-making process on the correspondence between supply and demand for Scenario 1 is shown in **Fig. 6.1**.

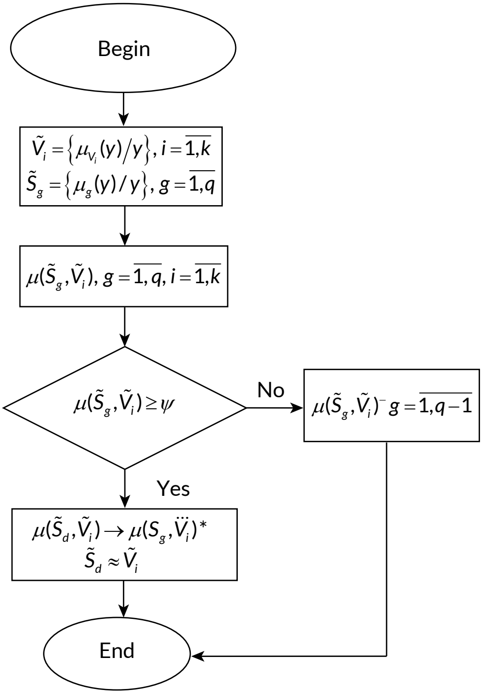

Fig. 6.1 Flowchart of the decision-making process on the correspondence between supply and demand for Scenario 1

Scenario 2. A few applicants (specialists) are eligible to the employer in accordance with the accepted measure of the similarity of the two fuzzy situations, i.e. "one fuzzy reference pattern – many fuzzy real patterns". That is, in this case, there is a set $\{\mu(\tilde{S}_g, \tilde{V}_i), g = \overline{1,\eta}, \eta \leq q)\}$, the elements of which satisfy the following condition: $(\mu(\tilde{S}_g, \tilde{V}_i), g = \overline{1,\eta}) \geq \psi$.

In this case, the employer, acting as an expert (DM), can be offered various methods for decision making:

Scenario 2.1. The task of making decisions on the correspondence of supply and demand is reduced to the comparison of the proximity of the reference and real situations in terms of the degree of possession of the criteria that characterize a certain professional group or specialty. The best alternative (applicant) is that, who has the greatest proximity rate by the coincidence of criteria and the degree of their possession.

In this case, the sought is the real situation, which provides the maximum value in terms of the degree of reference similarity, i.e.

$$\mu(\tilde{S}_d,\tilde{V}_i)^* = \max(\mu(\tilde{S}_g,\tilde{V}_i),\ g=\overline{1,\eta},\ \tilde{S}_d \in \left\{\tilde{S}_g,\ g=\overline{1,\eta}\right\}. \tag{6.13}$$

Scenario 2.2. The task of decision making is reduced to a multicriteria choice of the best solution (alternative), taking into account the relative importance of the criteria characterizing the specialists [38].

In this case, the task of decision-making is implemented in accordance with the following steps:

Step 1. The coefficients of relative importance of the indicators shall be defined [38, 39].

Assume that:

– $\omega_j,\ j=\overline{1,n}$ – coefficients of relative importance of indicators characterizing the criterion L;

– $\omega_f, f=\overline{1,m}$ – coefficients of relative importance of indicators characterizing the criterion C;

– $\omega_\gamma, \gamma=\overline{1,p}$ – coefficients of relative importance of indicators characterizing the criterion U.

Step 2. Based on the aggregation of the degrees of possession of individual indicators (i.e. $\mu_{l_{gj}}(\tilde{S}_g,\tilde{V}_i),\ j=\overline{1,n},\ \mu_{c_{gf}}(\tilde{S}_g,\tilde{V}_i), f=\overline{1,m},\ \mu_{u_{g\gamma}}(\tilde{S}_g,\tilde{V}_i), \gamma=\overline{1,p}$), the specific specialists $S_g, g=\overline{1,\eta}$ determine the degree of similarity of fuzzy real situations (supply) with the reference situation (demand) by the following step [40]:

Step 2.1. Based on the "convolution" $\mu_{l_{gj}}(\tilde{S}_g,\tilde{V}_i),\ j=\overline{1,n},$ the degree of similarity between real and reference situations is determined by personal characteristics (L)

$$\mu_L(\tilde{S}_g,\tilde{V}_i)=\sum_{j=1}^{n} w_j \mu_{l_j}(\tilde{S}_g,\tilde{V}_i).$$

Step 2.2. Based on the "convolution" $\mu_{c_{gf}}(\tilde{S}_g,\tilde{V}_i), f=\overline{1,m}$ – the degree of similarity between real and reference situations is determined in terms of competences (C)

$$\mu_C(\tilde{S}_g,\tilde{V}_i)=\sum_{f=1}^{m} w_f \mu_{c_f}(\tilde{S}_g,\tilde{V}_i).$$

Step 2.3. Based on the "convolution" $\mu_{u_{g\gamma}}(\tilde{S}_g, \tilde{V}_i), \gamma = \overline{1, p}$ – the degree of similarity between real and reference situations is determined through the prism of the requirements for the vacancy *U*

$$\mu_U(\tilde{S}_g, \tilde{V}_i) = \sum_{\gamma=1}^{p} w_\gamma \mu_{u_\gamma}(\tilde{S}_g, \tilde{V}_i).$$

Step 2.4. Based on the obtained results and coefficients of relative importance *L*, *C* and *U* – w_L, w_C, w_U, the similarity rates of the real situation with the reference ones are determined

$$\mu_w(\tilde{S}_g, \tilde{V}_i) = \omega_L \cdot \mu_L(\tilde{S}_g, \tilde{V}_i) + \omega_C \cdot \mu_C(\tilde{S}_g, \tilde{V}_i) + \omega_U \cdot \mu_U(\tilde{S}_g, \tilde{V}_i).$$

Step 3. Fuzzy real situation with the maximum value is chosen

$$\varphi(\tilde{S}_g, \tilde{V}_i)^* = \max\left\{\varphi(\tilde{S}_g, \tilde{V}_i), g = \overline{1, \eta}\right\}.$$

The selected fuzzy real situation corresponds to the search pattern of the applicant, who has the greatest degree of similarity with the reference pattern of the vacancy, and is accepted as the best solution.

Scenario 2.3. The list of evaluation criteria is extended, and the input situations are re-defined (re-examined) and the recognition procedures are repeated.

A flowchart of the decision-making process on the correspondence between supply and demand for Scenario 2 is presented in **Fig. 6.2**.

According to this proposed algorithm, empirical experiments are implemented to solve the problem of hiring a programmer-engineer in [31] and a pediatrician in [38].

Scenario 3. "Many fuzzy reference patterns – one fuzzy real pattern". In this case, there is an inverse task: a subset of fuzzy reference situations (alternatives) is presented, which is represented, out of which a specialist has to make a choice according to his/her preferences. In this case, a professional is DM. According to the preferences of the latter, there can be the variants of Scenario 3 listed below.

Scenario 3.1. The proximity rate of the claims of the specialist with the green criteria characterizing the employment in the certain green specialty shall be compared, and decision shall be made on the greatest coincidence of the degree of possession of the criteria.

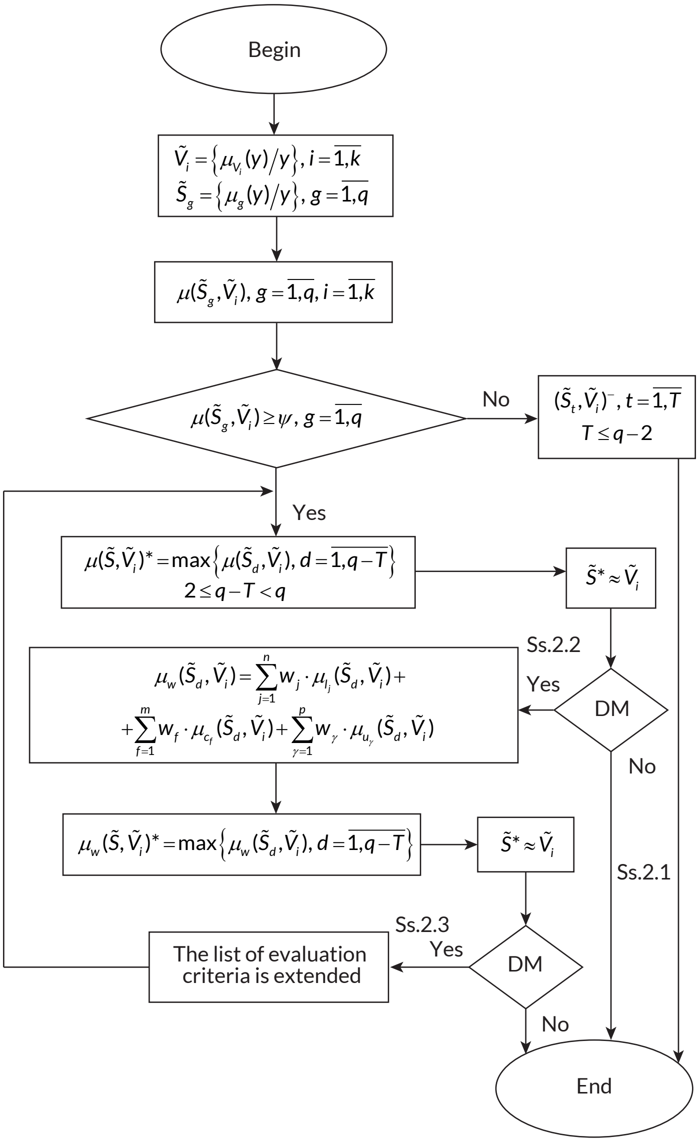

Fig. 6.2 Flowchart of the decision-making process on the correspondence between supply and demand for Scenario 2

The task of decision-making is reduced to the comparison of the similarities between real and standard situations in terms of the proximity rate of the conditions offered by employers and the claims of the applicant. The best vacancy has the greatest degree of similarity by the coincidence of green criteria that characterize the conditions offered by employers, and the applicant's claims. Thus, it is possible to assume that:

$$\mu(\tilde{S}_d,\tilde{V}_z)=\max\left\{\mu(\tilde{S}_g,\tilde{V}_z),\, z=\overline{1,f},\, g=\overline{1,q}\right\},\, V_z\in\left\{V_i,\, i=\overline{1,k}\right\},$$
$$S_d\in\left\{S_g,\, g=\overline{1,q}\right\},\, 2\le f<k.$$

In this case, the pair with the maximum value of the degree of fuzzy similarity situations is defined by the following formula

$$\mu(\tilde{S}_d,\tilde{V}_z)^*=\max\left\{\mu_U(\tilde{S}_d,\tilde{V}_z),\, z=\overline{1,f}\right\}.$$

The fuzzy reference green situation is accepted as the best solution, which is corresponding to the green search pattern of the vacancy that has the greatest degree of green similarity with the applicant's real pattern.

Scenario 3.2. The task of decision-making shall be reduced to the multi-objective task of choosing the best solution, taking into account the relative importance of green criteria characterizing the preferences of a specialist (*U*), expressed in the form of his/her requirements for a specialized green vacancy.

In this case, if $\omega_\gamma, \gamma=\overline{1,p}$ is the coefficients of the relative importance of green indicators characterizing the criterion *U*, then a fuzzy reference situation that has the greatest degree of similarity (greenness) with the applicant's real pattern is determined based on the following formula

$$\mu(\tilde{S}_d,\tilde{V}_z)^*=\max\left\{\sum_{\gamma=1}^{p} w_\gamma\cdot\mu_{u_\gamma}(\tilde{S}_d,\tilde{V}_z),\, z=\overline{1,f}\right\}.$$

The selected pair is taken as the best solution.

Scenario 3.3. The list of green criteria for the workplace assessment shall be expanded, furthermore, the input situations shall be re-defined (re-examined) and the recognition procedure shall be repeated using formulas (6.11) or (6.12).

A flowchart of the decision-making process on the correspondence between supply and demand for Scenario 3 is presented in **Fig. 6.3**.

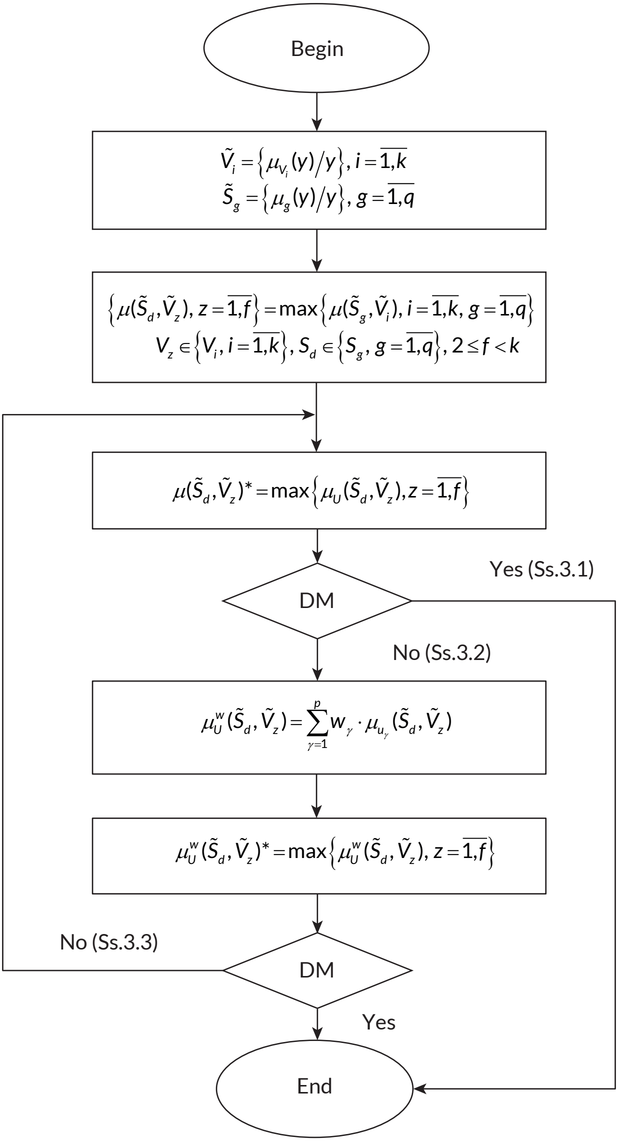

Fig. 6.3 Flowchart of the decision-making process on the correspondence between supply and demand for Scenario 3

6.4 Example of implementation of the methodology for hiring a specialist for a green vacancy

Let's consider the application of the proposed methodology using the example of solving the problem of real selection and hiring for a specific green vacancy of an IT engineer for land resources management.

Let a vacancy of an IT engineer for land resources management be – *V*, for which four IT specialists are applying – S_1, S_2, S_3, S_4. Let's consider the stages of implementing the problem of making decisions on selecting candidates for this vacancy from four applicants, using the degree of their fuzzy equality to determine the proximity of two situations:

Stage 1. Definition of a reference situational model of a vacancy, which comes down to the selection of indicators characterizing the employers' requirements for the vacancy. To form a system of indicators characterizing vacancies, information on hiring an IT engineer for land resources management from recruiting sites is used [8, 41].

Indicators system for vacancy *V*:

Personal qualities (*L*):

– communication skills (l_1);

– systemic thinking (l_2);

– work on yourself, desire to develop (l_3).

Competencies, knowledge and skills (*C*):

– level of professional knowledge in the specialty "IT engineer for land resource management" in accordance with the university diploma (c_1);

– knowledge of the development of GIS platforms to maintain a land registry and accounting, monitor (c_2);

– knowledge in the field of geodesy, remote sensing, geographic information systems (c_3);

– practical skills in using the capabilities of geographic information systems for land resource management (c_4).

Requirements and conditions of the vacancy (*U*):

– minimum 1 year of practical work (u_1);

– certificate in the course of green transition in land resource management (u_2);

– fluency in the national and English languages (u_3).

Stage 2. To determine the degree of possession of individual indicators by applicants, it is necessary to formalize the indicators, i.e., it is necessary to operate with linguistic variables and their values [32]. **Table 6.1** demonstrates 5-level values of the linguistic variable "communicability" and the corresponding ranges of change of fuzzy degrees of possession of this indicator in the interval [0, 1].

Table 6.1 Fuzzification of the indicator "communicability"

Gradations of the indicator "communicability"	Linguistic assessment	The range of change of fuzzy degrees in the interval [0, 1]
Very sociable	Excellent	[0.95–1]
Communicative	Good	[0.8–0.94]
Weakly sociable	Normal	[0.5–0.79]
Unsociable	Satisfactory	[0.26–0.49]
Withdrawn	Bad	[0–0.25]

Stage 3. Linguistic assessments of candidates for vacancy *V* are given in **Table 6.2**.

Table 6.2 Linguistic assessments of candidates for vacancy *V*

Indicators characterizing the vacancy *V*	Applicants			
	S_1	S_2	S_3	S_4
Personal qualities (*L*):				
Communication skills (l_1)	Excellent	Good	Good	Normal
Systemic thinking (l_2)	Good	Good	Good	Good
Work on yourself, desire to develop (l_3)	Good	Good	Good	Good
Competencies, knowledge and skills (*C*):				
Level of professional knowledge in the specialty "IT engineer for land resource management" in accordance with the university diploma (c_1)	Excellent	Excellent	Good	Excellent
Knowledge of the development of GIS platforms to maintain a land registry and accounting, monitor (c_2)	Good	Good	Normal	Good
Knowledge in the field of geodesy, remote sensing, geographic information systems (c_3)	Excellent	Excellent	Good	Good
Practical skills in using the capabilities of geographic information systems for land resource management (c_4)	Good	Excellent	Good	Normal
Requirements and conditions of the vacancy (*U*):				
Minimum 1 year of practical work (u_1)	Good	Good	Excellent	Excellent
Certificate in the course of green transition in land resource management (u_2)	Good	Good	Excellent	Excellent
Fluency in the national and English languages (u_3)	Excellent	Excellent	Good	Good

Table 6.3 presents the degrees of possession of the candidates with the indicators characterizing the vacancy *V*.

Table 6.3 Degrees of possession of the candidates with the indicators (membership function values) characterizing the vacancy *V*

Indicators characterizing the vacancy *V*	Applicants			
	S_1	S_2	S_3	S_4
Personal qualities (*L*):				
Communication skills (l_1)	0.97	0.88	0.82	0.65
Systemic thinking (l_2)	0.89	0.85	0.89	0.82
Work on yourself, desire to develop (l_3)	0.87	0.80	0.70	0.90
Competencies, knowledge and skills (*C*):				
Level of professional knowledge in the specialty "IT engineer for land resource management" in accordance with the university diploma (c_1)	0.98	0.95	0.82	0.97
Knowledge of the development of GIS platforms to maintain a land registry and accounting, monitor (c_2)	0.90	0.84	0.75	0.88
Knowledge in the field of geodesy, remote sensing, geographic information systems (c_3)	0.95	0.97	0.80	0.82
Practical skills in using the capabilities of geographic information systems for land resource management (c_4)	0.82	0.95	0.90	0.70
Requirements and conditions of the vacancy (*U*):				
Minimum 1 year of practical work (u_1)	0.90	0.94	0.97	0.96
Certificate in the course of green transition in land resource management (u_2)	0.82	0.82	0.97	0.95
Fluency in the national and English languages (u_3)	0.95	0.95	0.80	0.88

Based on **Table 6.3** and formula (6.10), fuzzy real situations are formed, i.e. fuzzy images of applicants for vacancy *V*:

$$\tilde{S}_1 = \begin{Bmatrix} 0.97/l_1; 0.89/l_2; 0.87/l_3; 0.98/c_1; 0.9/c_2; 0.95/c_3; \\ 0.82/c_4; 0.9/u_1; 0.82/u_2; 0.95/u_3 \end{Bmatrix},$$

$$\tilde{S}_2 = \begin{Bmatrix} 0.88/l_1; 0.85/l_2; 0.8/l_3; 0.95/c_1; 0.84/c_2; 0.97/c_3; \\ 0.95/c_4; 0.94/u_1; 0.82/u_2; 0.95/u_3 \end{Bmatrix},$$

$$\tilde{S}_3=\begin{Bmatrix}0.82/l_1;0.89/l_2;0.7/l_3;0.82/c_1;0.75/c_2;0.8/c_3;\\0.9/c_4;0.97/u_1;0.97/u_2;0.8/u_3\end{Bmatrix},$$

$$\tilde{S}_4=\begin{Bmatrix}0.65/l_1;0.82/l_2;0.9/l_3;0.97/c_1;0.88/c_2;0.82/c_3;\\0.7/c_4;0.96/u_1;0.95/u_2;0.88/u_3\end{Bmatrix}.$$

The reference fuzzy image of vacancy V is described as follows

$$\tilde{V}=\{1/l_1;1/l_2;1/l_3;1/c_1;1/c_2;1/c_3;1/c_4;1/u_1;1/u_2;1/u_3\}.$$

Stage 4. Using formula (6.12), the degrees of fuzzy equality of the reference $\tilde{V}$ and real situations $\tilde{S}_1, \tilde{S}_2, \tilde{S}_3, \tilde{S}_4$ are determined:

– by personal indicators (L):

$$\mu_L(\tilde{V},\tilde{S}_1)=0.87;\ \mu_L(\tilde{V},\tilde{S}_2)=0.8;\ \mu_L(\tilde{V},\tilde{S}_3)=0.70;\ \mu_L(\tilde{V},\tilde{S}_4)=0.65;$$

– in terms of competencies (C):

$$\mu_C(\tilde{V},\tilde{S}_1)=0.82;\ \mu_C(\tilde{V},\tilde{S}_2)=0.84;\ \mu_C(\tilde{V},\tilde{S}_3)=0.75;\ \mu_C(\tilde{V},\tilde{S}_4)=0.7;$$

– through the prism of vacancy requirements (U):

$$\mu_U(\tilde{V},\tilde{S}_1)=0.82;\ \mu_U(\tilde{V},\tilde{S}_2)=0.82;\ \mu_U(\tilde{V},\tilde{S}_3)=0.8;\ \mu_U(\tilde{V},\tilde{S}_4)=0.88.$$

Based on the results obtained, the degree of fuzzy equality $\mu(\tilde{V},\tilde{S}_g),\ g=\overline{1,4}$ of the reference image of vacancy V and search images of real situations $\mu(\tilde{V},\tilde{S}_g),\ g=\overline{1,4}$ is determined:

$$\mu(\tilde{V},\tilde{S}_1)=\mu_L(\tilde{V},\tilde{S}_1)\&\mu_C(\tilde{V},\tilde{S}_1)\&\mu_U(\tilde{V},\tilde{S}_1)=0.87\&0.82\&0.82=0.82,$$

$$\mu(\tilde{V},\tilde{S}_2)=\mu_L(\tilde{V},\tilde{S}_2)\&\mu_C(\tilde{V},\tilde{S}_2)\&\mu_U(\tilde{V},\tilde{S}_2)=0.8\&0.84\&0.82=0.8,$$

$$\mu(\tilde{V},\tilde{S}_3)=\mu_L(\tilde{V},\tilde{S}_3)\&\mu_C(\tilde{V},\tilde{S}_3)\&\mu_U(\tilde{V},\tilde{S}_3)=0.7\&0.75\&0.8=0.7,$$

$$\mu(\tilde{V},\tilde{S}_4)=\mu_L(\tilde{V},\tilde{S}_4)\&\mu_C(\tilde{V},\tilde{S}_4)\&\mu_U(\tilde{V},\tilde{S}_4)=0.65\&0.7\&0.88=0.65.$$

Stage 5. The results obtained correspond to Scenario 2.1, i.e., in terms of the degree of fuzzy equality of the reference situation $\tilde{V}$ and real situations $\tilde{S}_1, \tilde{S}_2, \tilde{S}_3, \tilde{S}_4$, the closest is the real situation $\tilde{S}_1$ with the value $\mu(\tilde{V},\tilde{S}_1)=0.82$.

Thus, the real search image of the applicant S_1 has the maximum degree of proximity to the reference search image of the vacancy V and is the best solution.

6.5 Discussion of research results

The green transition, its demands for professional groups and specialties cause some changes in the structure of professions, the formation of the green segment of the labor market, the creation of workplaces requiring different degrees of greenness, the diverse greenness rates of the skills offered for these vacancies, and the creation of numerous uncertain green demand-supply relationships. In order to eliminate this uncertainty and reveal the real situation, this article proposed a comprehensive approach to intelligent management of human resources in the green segment of the labor market.

The new approach proposed in this article was based on:

1) fuzzy multicriteria assessment and ranking of alternatives for determining priority green professional groups and specialties;

2) decision-making methods in the context of priority specialties, allowing to take into account the entire spectrum of real and potential relationships between supply and demand in the labor market. The decision-making methods are based on fuzzy situational analysis and pattern recognition. The developed methods and algorithms for multi-scenario assessment of supply and demand, based on fuzzy situational analysis and pattern recognition, make it possible to make decisions on the degree of green compliance of supply and demand in the context of specific green professions or specialties from the standpoint of satisfying both the employer's requirements and the claims of specialists.

6.6 Conclusion

1. A new comprehensive approach to intelligent human resource management in the green segment of the labor market was proposed, allowing for the entire spectrum of real and potential relationships between green demand and green supply.

2. Multi-criteria individual and collective decision-making methods were developed referring to fuzzy relational model to determine the priority of green occupational groups and specialties in a dynamically changing labor market in green environment.

3. The problem statement of decision-making on the coordination of supply and demand for specialists in the context of a specific priority green profession or

specialty was presented, which was reduced to fuzzy pattern recognition. Pattern recognition was based on fuzzy situational analysis and determination of the green proximity rate of fuzzy situations. The degree of their fuzzy inclusion and fuzzy equality were used as the measures for assessing the proximity rate of two fuzzy situations.

4. Possible scenarios of the relationship between supply and demand were proposed, for each of which appropriate methods and algorithms for making decisions on the green compliance of supply and demand in the context of green professions and specialties most in demand in the labor market were developed.

5. The task can be developed by expanding the set of possible scenarios for matching supply and demand and developing appropriate decision-making methods.

6. A step-by-step implementation of the methodology for multi-scenario supply and demand management was implemented using the example of solving the problem of real selection and hiring for a specific green vacancy.

7. The proposed methodology for assessing green skills in the labor market ecologization environment is invariant for human resource management in various segments of the green economy, provided that it was adapted to the characteristics of the segment under study.

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CHAPTER 7

Shared use of transport as a component of the circular economy in relation to achieving sustainable development goals

Alla Karnaushenko
Lesia Kononenko
Viktoriia Petrenko
Yuliia Hlavatska
Nataliia Sysolina
Iryna Sysolina

Abstract

The study aims to substantiate the feasibility of implementing models of shared transport as a tool for applying the principles of circular economy (CE) in the context of achieving Sustainable Development Goals (SDGs), focusing on rural territorial communities in Ukraine. The paper proposes an assessment of the economic, environmental, and social effects of implementing shared transport programmes at the local level. Methods of case analysis, correlation analysis, logical generalization, and a structural-functional approach have been applied. Direct effects of car-sharing implementation in the Adzhamka territorial community have been calculated: a reduction of CO_2 emissions by 13.68 tons per year and an annual saving for users of up to 43,000 UAH. Three hypotheses regarding the effectiveness of the sharing transport model have been tested: it has been proven that it provides comprehensive sustainable development effects, depends on the digital readiness of the population, and is financially sustainable in a cooperative format. The study identified structural barriers to scaling the sharing economy (SE) in rural areas, including the digital divide and insufficient levels of social activity within communities. The potential of shared mobility models for rural regions in the post-war period has been summarized. An approach to assessing the viability of local models has been proposed, based on a combination of environmental indicators, household costs, and the level of digital inclusion.

The scientific novelty of the research lies in the combination of CE and SE concepts at the local level and the justification of shared transport's effects in rural territorial communities. Future research perspectives include a sociological study of

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the perception of sharing models among different population groups, a comparative analysis of communities with varying levels of digital maturity, and the integration of smart mobility into circular strategies.

The research has an applied and empirical nature.

Keywords

Circular economy, sustainable development, sharing economy, shared mobility, car sharing, digital transformation, rural communities, environmental impact, digital divide, cooperative models.

7.1 Introduction

In the 21st century, humanity has faced unprecedented global challenges, including the rapid depletion of natural resources, environmental degradation, anthropogenic climate change, and rising social inequality. These processes are primarily driven by the dominance of a linear economic model that focuses on one-sided consumption of resources under the principle of "take-make-dispose". In response to these systemic threats, the global scientific community and international political institutions, including the United Nations, are advocating for the transformation of economic development based on the CE principles. This paradigm entails closed loops of resource use, reduction in waste volumes, and minimization of negative environmental impact to achieve the SDGs.

CE, which combines economic feasibility with environmental responsibility, is a strategic foundation for building an innovative and inclusive future economy. However, despite the conceptual appeal and the widespread usage of relevant terminology in political and scientific discourse, the level of circularity in the global economy, according to the Circularity Gap Report 2024, remains critically low and shows a downward trend. It indicates the need to redirect attention from the normative to the applied level, particularly through the study of tools capable of ensuring the CE implementation principles at the local level.

One such tool is SE, which allows for increased efficiency in resource utilization without significant infrastructure investments. The study of transportation sharing models (in particular, car sharing) is becoming increasingly relevant as one of the most dynamic segments of SE, which has the potential to contribute to environmental, economic, and social benefits simultaneously. In rural areas, where access to infrastructure is limited and the level of digitalization remains inadequate, these models may become essential in ensuring a sustainable mobility environment and social integration, particularly for internally displaced persons in the context of the war in Ukraine.

The research aims to conceptualize and empirically substantiate the shared use of transport as an effective mechanism for implementing the CE principles in relation to achieving the SDGs, taking into account the socio-economic specifics of rural areas in Ukraine.

To achieve the set goal of the research, scientific hypotheses have been formulated, the verification of which allows for the identification of key factors influencing the effectiveness of implementing shared transport models in the context of the circular transformation of rural communities:

H_1: shared transport in rural areas can be an effective form of implementing the CE principles, providing ecological, social, and economic benefits simultaneously.

H_2: digital competencies and access to digital infrastructure are key prerequisites for successfully implementing SE models in rural environments.

H_3: a cooperative form of organization and inclusive participation of the local community ensure the financial viability and social legitimacy of shared transport programmes.

The methodological basis of the research is an interdisciplinary approach that combines elements of economic theory, sustainable development, digital transformations, sociology, and environmental management. This approach has enabled a comprehensive assessment of the potential of transport-sharing models as a tool for implementing the CE principles in relation to SDGs.

The research has been conducted in several stages using the following methods:

1. Analysis of literary sources and conceptual framework – a review of domestic and foreign scientific literature on CE, SE, digital transformation, and sustainable development has been conducted. A comparison of the 3R, 6R, and 9R models has been carried out, and the concept of SE has been systematized across various research approaches.

2. System-structural analysis has been used to identify the interconnections between the key elements of the CE concept, digitalization, and resource sharing within the structural transformation of consumption models. Particular attention has been given to studying interactions between the economic, ecological, and social subsystems.

3. Case method – a case study of the Adzhamka territorial community in the Kirovohrad region has been used to empirically verify hypotheses, analyzing the possibilities for implementing a transport sharing model. Economic costs and benefits, the population's digital readiness, the project's social significance, and its environmental impact have been evaluated.

4. Quantitative analysis – an assessment of the ecological effect (reduction of CO_2 emissions due to the use of electric transport), the economic impact for users

of various mobility models, and the amount of investment required for project implementation has been conducted.

5. Correlation analysis – to test the hypothesis regarding the increase in the proportion of car-sharing users among the global population, Pearson correlation coefficient has been used. It has revealed a strong positive relationship between the absolute and relative growth in the number of users of such services.

6. Methods of logical analysis and deduction have been applied in formulating hypotheses, substantiating conclusions, and interpreting the empirical results of the research in the context of the sustainable development of rural areas in Ukraine.

Thus, the combination of qualitative and quantitative research methods ensured the comprehensiveness of the analysis of shared transport as a tool for the circular transformation of the economy and allowed for verifiable conclusions regarding its effectiveness in the context of a rural community.

7.2 The SE model in the context of circular transformation

CE is essential for achieving the SDGs in the agricultural sector. Integrating innovative methods and technologies that minimize the consumption of limited resources, encourage their replacement with renewable ones, prevent waste, and promote reuse and recycling is possible. Systematic implementation of such approaches enables a qualitative shift from focusing on production efficiency to prioritizing resource use efficiency.

Blockchain technology facilitates the introduction of the CE principles in the agricultural sector. It helps optimize forming "production-consumption" chains to enhance resource use efficiency [1].

Organic farming is one of the key directions for implementing the CE principles. Traditionally, farming enterprises predominantly apply organic agriculture.

Society increasingly recognizes that the depletion of natural resources, the deterioration of ecosystems, and the formation of harmful substances, including waste, pollutants, and greenhouse gas emissions, are directly caused by the dominant production and consumption paradigms. In particular, a significant impact on biodiversity loss, accounting for up to 90% of global indicators, is associated with the extraction and processing of primary raw materials [2]. In response to these challenges, there is a growing interest in CE as an alternative to the linear model.

At the same time, in practice, implementing circular approaches in various sectors, including agriculture, is accompanied by significant challenges, highlighting the need to search for adaptive models capable of functioning under limited resources, inadequate infrastructure, and changing consumer behavior.

Despite broad support at the conceptual level, implementing the CE principles faces considerable difficulties in practice. This concept often remains largely theoretical without proper scaling of implementation.

According to the Circularity Gap Report 2024, the share of circularity in the global economy decreased to 7.2% in 2023 [3, 4], compared to 8.6% in 2020 and 9.1% in 2018 [5]. It underscores that despite the growing interest in CE, its practical implementation is still not progressing quickly enough to overcome the overall negative trend.

Researchers note that there are various obstacles to CE implementing, including the need for greater financial support from governments, difficulties in creating effective circular supply chains, economic challenges related to consumer behavior, and challenges in product redesign. Significant investments in technology and infrastructure to support recycling, recovery, and reverse logistics are also crucial aspects. In this context, a critical model of CE that does not require substantial funds for implementation and positively impacts society's perception of the CE philosophy is SE.

The term "sharing economy" is increasingly encountered in international scientific literature. Numerous studies confirm a close relationship between the sharing and circular economies. This interrelationship is primarily determined by sharing, supporting the CE principles, and promoting more sustainable and rational consumption. The objective prerequisites for implementing the "sharing" concept are consumers' established perception of it and the presence of business entities that intend to and enforce such business initiatives [6].

The term "sharing economy" was introduced in 1978 by M. Felson and J. L. Spaeth [7]. It gained its popularity in the early 21st century and is associated with the name of L. Lessig [8, 9]. This scholar was one of the first to use this term in a modern context within professional literature.

Depending on the context, "sharing" can mean "to divide": as in splitting into equal parts; as distribution; as a form of collective ownership; as a process of communication; or as a form of individual embodiment in the network [10]. In English-language works, this term continuously shifts in meaning, which is linked to SE development and the dissemination of information regarding opportunities to participate in it on social media. Despite the lack of a direct connection between the terms "shared use" and "economy", the term "sharing economy" is commonly used and describes "a growing model of consumer behavior".

The practical implementation of the SE principles and models potentially provides both economic and social as well as environmental effects:

– it promotes savings and/or forms the basis of business;

– it alters consumer behavior;

– it reduces resource usage;

– it encourages more sustainable consumption and sustainable economic growth.

The interpretation of the term "sharing economy" is ambiguous. The practical implementation of the SE principles also involves various consumer practices and organizational models. The scientific literature presents different approaches to their distinction within SE according to the fields of scientific research (**Table 7.1**).

Table 7.1 Approaches to interpreting the term "sharing economy" and its organizational models

Author (source)	Explanation and typical features
M. Trigkas, G. Karagouni, M. Tsitsoni (2025) [6]	Part of the circular economy, based on creating value through common and open resources in ways that balance personal interests with the welfare of the broader community
P. Chen, Y. Wu, Z. Chu (2025) [11]	The use and exchange of unused resources or services through online platforms supported by the Internet and digital technologies, thereby achieving mutual utilization and shared access to resources and services
Y. Feng, R. Xu (2025) [12]	The product of the digital revolution, developing alongside the Internet
T. Surmacz et al. (2024) [13]	The internet is a central medium of communication and sharing with others, providing effective access to underutilized products
A. A. Singh (2022) [14]	The socio-economic structure in which people are willing to share their own "social" products and services, focusing on both the social and economic components of the concept
Z. Wu, W. Zhou, A. Yu (2023) [15]	Its mechanism is collaboration, which enhances the overall efficiency and reliability of the system
A. Sundararajan (2017) [16]	Economic and business model: one in which people have free access to resources, such as goods or services, through rental, exchange, leasing, or sale; which encourages maximum utilization of resources, often leading to savings and waste reduction
A. I. Szymańska (2021) [17]	This is an alternative model of consumption that is based on access to goods without the necessity of owning them

Source: created on the basis of [6, 11–17]

SE is related to both CE and the SDGs direct implementation. Many interpretations emphasize the peculiarities of ownership relations in implementing the SE principles. It includes the dispersion of such owner powers as the right to possess and use, restrictions on ownership rights, and the transfer to users of usage rights (leasing). The legal aspects exhibit significant differences depending on the qualitative characteristics of a SE model, whether commercial or non-commercial.

SE replaces ownership with access, promoting sustainable development by optimizing consumption and utilising resources that harm the environment. The shared use of resources and services reduces the consumption of raw materials and energy, a decrease in emissions and waste disposal costs, thus minimizing the negative impact on the environment.

An important aspect is the direct connection between SE and the digitalization processes, and the presence of relevant digital platforms.

SE contributes to the CE goals and principles. Theoretically, reuse based on the application of shared access is one of the least resource, information-intensive, and labor-intensive ways to enhance product consumption efficiency. Thus, sharing products (services) embodies the principle of reuse within CE and underpins several other goals, such as management instead of ownership and resource use efficiency. There is a wide range of sharing practices and business models in practice.

The study of digital sharing platforms within CE context is just beginning to develop. Despite a broad spectrum of business initiatives implementing sharing practices that have emerged recently, the existing literature primarily focuses on the accommodation and mobility sectors, with prominent examples including Airbnb and Uber. However, many scholars hypothesize about why people contribute to SE, whether as consumers and/or providers of goods and services.

The SE interpretation and its expected effects by scholars is ambiguous. Given the diversity of various forms of digital exchange platforms and the conflicting assessments of what these practices contribute, researchers raise questions about the reality of providers' aspirations towards environmental, social, and the CE economic goals and principles, as well as the structuring of business models accordingly.

Let's consider digitalization processes to be a prerequisite for SE developing. Currently, most scholarly papers dedicated to SE examine the issue of the experience of implementing SE models in cities within the context of enhancing quality of life and sustainable urban economic development. SE primarily develops in urban areas due to high population density and the intensity of social interactions, which create favorable conditions for startups in this field. The spread of SE business models to rural areas is limited by lower population density and a lower concentration of unused assets. However, there is significant potential for developing SE in rural areas. In our opinion, its implementation is hindered in Ukraine by a low level of business culture and digitalization in the countryside.

The global SE market was valued at 261,3 billion USD in 2024 and is projected to reach 3181,21 billion USD by 2033, growing at an average rate of 32.01% per year. According to another forecast (the global market for SE was valued at a 260,36 billion USD in 2024), it will steadily grow and reach 3185,37 billion USD by 2033, maintaining an average annual growth rate of 32.08% from 2025 to 2033 [18].

The lack of information at the national level complicates the ability to assess the size of SE market in Ukraine. However, an analysis of the available data and trends indicates active development of various sharing models that are becoming increasingly popular among the population of Ukraine. The main segments characterized by significant growth dynamics include:

– transport services, particularly car sharing models;

– the short-term rental housing market, including peer-to-peer platforms;

– spaces for collaborative work, known as co-working centers.

SE is viewed as a crucial factor for Ukraine's economic development and the enhancement of its competitiveness. For the successful development of this sector, a favorable legislative environment and an advanced digital infrastructure are necessary.

Kyiv ranks among the top ten cities by the SE development index. Co-living spaces are actively developing in Kyiv and are becoming increasingly popular. The founder of the co-living network Vilnyy believes that within 5 to 10 years, co-living will become very widespread in Ukraine. Given the need to provide housing for those affected by the war, who have suffered destruction and require relocation, as well as the overall increase in demand for flexible and affordable living options, it can be argued that SE, particularly co-living, has significant potential for growth in Ukraine in the coming years. It is especially relevant for rural areas, where, despite a considerable number of registered internally displaced persons around 20% of the total IDP population, which as of March 2025 exceeds 4,6 million, there is often a lack of shelters.

In theory and practice, there is a gap between the general access to goods and services in SE. It is related to the dependency of access and the level of positive perception of SE on income, education, age, etc. Furthermore, a firm reliance on information and communication technologies implies that factors such as the availability of electronic devices, internet connectivity, and digital literacy can create barriers to online exchange platforms, particularly relevant for rural areas in Ukraine.

Currently, sustainable rural development cannot be considered in isolation from digitization. For instance, "ICT4D" – "digital-for-development" is widely used today. Although the term "ICT4D" was first mentioned in the 1960s, contemporary scholars point to a new phase in their development characterized by such dynamic and profound transformation that it warrants discussion of a radical change in the role of digital technologies and the emergence of a new paradigm of "digital-for-development".

Today, "ICT4D" is the most critical component of rural development: information and communication technologies (ICT) have nearly complete geographical and demographic coverage; they are used in all areas of human life (in households; in data collection and processing in business; in the decision-making process; directly in agricultural production, etc.). These technologies are crucial for SE development. It implies access to technology and the possession of technological literacy by all members of society, which is currently problematic for Ukraine. The issue also extends to the existence of the digital divide, which is calculated as the difference (ratio) between the access opportunities of different individuals to the internet and digital technologies. Technological and social factors typically determine the causes of the digital divide. They are driven mainly by insufficient access to ICT and a lack of digital skills, the development of which is one of the most essential elements for future full and active participation in social life. According to the International Telecommunication Union (ITU) "Facts and Figures 2023", the steady but uneven progress in global internet connectivity highlights the presence of a digital divide [19]. For instance, in 2023, 81% of urban residents worldwide had internet access, whereas in rural areas this figure was only 50% of the population; respectively, in 2024, these figures are projected to be 83% and 48%. The gap between urban and rural areas, measured as the ratio of these two percentages, has remained stable in recent years: 1.7 in 2020, 1.6 in 2023, and 1.7 in 2024.

A problem for rural areas and the agricultural sector is the low level of digital literacy among the population. According to a sample survey, 61% of interviewed leaders of farming enterprises acknowledge the insufficient level of digital maturity of their operations and critically assess the level of digital competencies as personal and among employees [20].

The digital divide is observed between rural and urban residents and employees of agricultural holdings and other economic entities. Unlike large agricultural formations, Ukrainian smallholders focus on the domestic market, which means they currently ensure the country's food security and improve living standards in rural areas. Small agricultural enterprises represent a model of village-preserving business practice and are fundamental to the comprehensive sustainable development of rural territories and the maintenance of rural settlement networks. However, agricultural producers who adhere to this model face significant challenges related to material and technical support, staffing, increased production costs, and the lack of sales markets. The prospects for solving these problems are connected, among other things, to implementing a SE model. For instance, the shared use of equipment, including drones, and establishing infrastructure based on cooperation (supply-storage-processing) are also in line with the SE principles. The implementation of the SE model is directly conditioned by the development of digital competencies among members of farming households, owners, and agribusiness employees within "the learning region" concept framework. Accordingly, let's view the development of digital competencies as both a prerequisite for the effective implementation of "the learning region" concept and as a tool for the competitiveness of small agribusinesses, which is particularly relevant in the context of revitalizing business and ensuring sustainable rural development in the post-war period. Furthermore, the development of digital competencies is a prerequisite for the practical realization of the lifelong learning concept [21] (which pertains to economic literacy, the ability to utilize digital platforms, and positive perception and engagement with the SE model) and for ensuring the preservation and development of small agricultural producers.

Let's align ourselves with the position of researchers regarding the priority of developing individual, family, and small to medium-sized agricultural enterprises as the foundation for ensuring sustainable rural development and the preservation of the settlement network. In this context, researchers identify the need to direct agricultural policy towards stimulating the entrepreneurial potential of landowners, which is impossible without the formation of digital competencies. It entails the partnership involvement of the state, business, civil society (especially local communities), and educational institutions (of all levels), particularly in the context of SE establishment. It relates to the social transformation in rural areas.

The issues of sustainable rural development in European countries are similar to those within the country (migration, urbanization, etc.). However, in Ukraine, these problems are more profound and are exacerbated by the ongoing military actions. Most researchers see the resolution of these issues and the source of rural development in social innovations. Many foreign scholars often link studies aimed at forming an optimal rural development model to local and extra local networks. Regarding local networks, the cooperation of local communities with entities such as local business representatives, non-governmental organizations, and educational institutions is considered. This cooperation is explicitly organized to ensure sustainable rural development. The SE model aligns with these targeted directions.

It is traditional for researchers to argue for the necessity of implementing a model of innovative development that involves collaboration between business, government, education, and the community of local territorial society ("quadruple helix"). This model has proven successful in emerging and disseminating social innovations aimed at sustainable rural development and can be used as a foundation for implementing the SE principles.

Digitization is a fundamental prerequisite for SE development. Despite the global growth of this direction, its spread in Ukraine, particularly in rural areas, is hindered by the digital divide and a low level of digital literacy. At the same time, SE has significant potential to support small agricultural businesses and address socio-economic issues. One promising area of SE in rural areas is the shared use of transport, which provides environmental, economic, and social benefits.

7.3 The programme for shared transport use in rural areas: environmental, social and economic effects

The most widespread model of SE in the world at present is shared mobility services, such as car sharing, bike sharing, and electric scooter rentals. However, experts emphasize that most companies providing such services cease their operations within five years or earlier. This fact contradicts the need to reduce emissions, with expectations for achieving these goals directly linked to mobility. Shared mobility involves replacing transport ownership with the opportunity to utilize shared resources as needed. In the context of Ukraine's Euro-integration and the need to implement the "Smart and Sustainable Mobility" strategy, it is fitting to examine the positive experiences and challenges faced abroad, assess the state and prospects for the development of shared mobility services, and identify ways to implement them in Ukraine.

Car sharing is an effective tool for ensuring sustainable urban mobility. Evidence shows that its usage contributes to a decrease in the number of private vehicle owners and users, reducing greenhouse gas emissions. It accounts for the steady growth in car-sharing users worldwide. It is predicted that in 2029 their numbers will exceed 68 million individuals [22]. However, these are absolute figures: while the number of car-sharing users is increasing, so is the population. **Table 7.2** and **Fig. 7.1** provide the dynamics of the share of car-sharing users globally.

Table 7.2 The number of car-sharing users worldwide from 2017 to 2023, with a forecast up to 2029

Years	Number of users in millions	World population in billions of people	%
2017	36,04	7,646	0.47
2018	38,55	7,73	0.50
2019	41,6	7,811	0.53
2020	44,69	7,887	0.57
2021	47,91	7,954	0.60
2022	50,33	8,021	0.63
2023	54,89	8,092	0.68
2024	57,06	8,162	0.70
2025	59,31	8,232	0.72
2026	61,49	8,301	0.74
2027	63,68	8,369	0.76
2028	65,92	8,437	0.78
2029	68,19	8,503	0.80

Source: developed by the authors based on [22, 23]

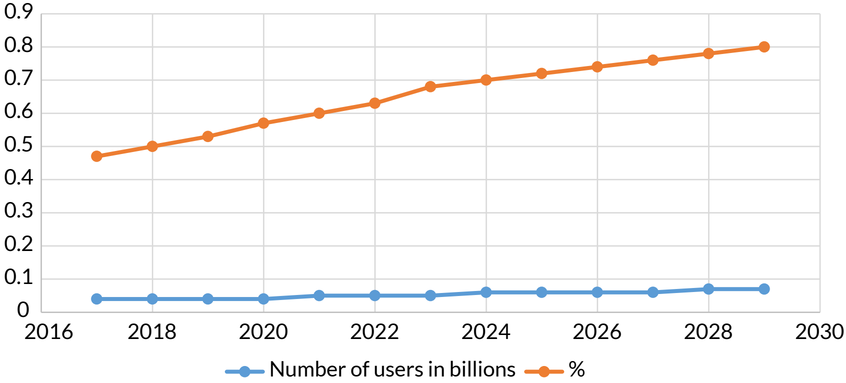

Fig. 7.1 The number of car-sharing users worldwide from 2017 to 2023, with a forecast to 2029
Source: developed by the authors based on [22, 23]

The data in **Table 7.2** and **Fig. 7.1** indicate a stable increase in car-sharing users. However, the percentage of such users remains relatively low.

To quantitatively assess the relationship between the number of car-sharing users worldwide and their prevalence among the global population, it is possible to conduct a correlation analysis of actual data from 2017 to 2023 [22, 23]. To determine the strength and direction of the linear relationship between these two indicators, Pearson correlation coefficient (*r*) was calculated using the formula

$$r=\frac{\sum\left[(x_i-\bar{x})(y_i-\bar{y})\right]}{\sqrt{\left[\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2\right]}},$$

where x_i – the number of car-sharing users in millions; $\bar{x}$ – the average number of users (≈ 44,86 million); y_i – the percentage of users relative to the world population; $\bar{y}$ – the average percentage of users (≈ 0.569%).

The calculations based on the actual data from the table showed the following sums

$$\sum\left[(x_i-\bar{x})(y_i-\bar{y})\right]\approx 2.976,\ \sum(x_i-\bar{x})^2\approx 268.1,\ \sum(y_i-\bar{y})^2\approx 0.033.$$

Substituting these values into the formula gives

$$r=\frac{2.976}{\sqrt{268.1\cdot 0.033}},\ r=\frac{2.976}{\sqrt{8.8473}},\ r=\frac{2.976}{2.974},\ r\approx 0.999.$$

The obtained correlation coefficient is 0.999. This value is extraordinarily high and approaches 1, indicating a virtually perfect linear relationship between the number of car-sharing users worldwide and the percentage of the global population that uses these services. In other words, during the analyzed period, each significant increase in the total number of people using car-sharing has been accompanied by a proportional rise in the share of these users within the overall structure of the global population. It confirms a stable and pronounced trend of increasing popularity of car sharing globally, alongside the Earth's population growth. Thus, it can be asserted that car sharing not only attracts new users in absolute terms but also becomes an increasingly prevalent mode of transport relative to the total number of people on the planet.

It should be noted that car sharing and car rental are fundamentally different in terms of service provision principles. Both services allow users to access a vehicle that is not privately owned, while maintaining a high level of interpersonal anonymity. However, car sharing differs from car rental in that it is carried out using digital technologies, is more flexible in terms of access, and, therefore, differs in more flexible access modes and pricing strategies.

Today, the five main business models of car sharing are identified (**Fig. 7.2**).

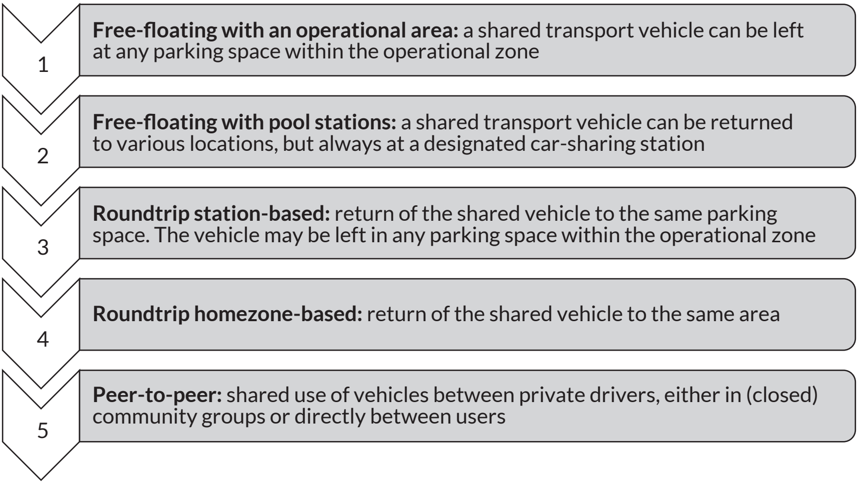

Fig. 7.2 Main business models of car sharing
Source: developed by the authors based on [24]

Today, car sharing is generally seen as a tool for reducing traffic congestion, decreasing the demand for parking spaces, and freeing up street space for active mobility in cities and as an essential element of sustainable urban development. However, car sharing implementation in rural areas is less developed and has particularities. Rural areas are characterized by low population density and significant distances between public facilities such as schools, shops, and medical establishments. These characteristics complicate the provision of public transport services at a level that would be satisfactory for rural residents and economically viable. As a result, rural residents without their vehicles often encounter difficulties with mobility and access to essential social services. In other words, the overall effectiveness of transport systems in rural areas usually fails to provide all rural residents with adequate accessibility, leading to social isolation.

Today, the implementation of car sharing in Ukraine occurs in the context of large-scale military actions, which impact all areas of life, including the mobility of the population. Those territories of Ukraine that are not in areas of active combat have become a refuge for a significant number of internally displaced persons, leading to increased pressure on the existing transport infrastructure. Concurrently, activating the volunteer movement to assist the military, displaced individuals, and the civilian population is creating new mobility needs. Under such conditions, the car-sharing concept may hold particular significance, providing a flexible and accessible solution for the transportation of residents and internally displaced persons and meeting the transport needs of volunteer initiatives. However, there are significant security, economic stability, and logistics challenges. Considering these specific features, namely the impact of migration processes, volunteer activities, and general instability, it is possible to choose the settlement of Adzhamka in the Kirovohrad region for analysis. The research in this locality may reveal specific needs and potential for implementing shared transport models in rural areas that align with the conditions of wartime and post-war recovery in Ukraine.

Adzhamka is a rural community with a population of over 6,000 people, of which approximately 1,800 constitute the economically active population. A distinctive feature of the community is the reception of a significant number of internally displaced persons, the number of which exceeded 300 as of July 2025. An active labor migration of a considerable part of the working-age population to the regional center, Kropyvnytskyi, indicates a need to establish transport connections. Thanks to its natural and historical resources, the community possesses certain tourist potential, which creates the conditions for developing green and ethnographic tourism. The area of the community is substantial (292,0 km^2), and the settlements are dispersed, emphasizing the importance of ensuring mobility for residents. The level of digitalization in the community is assessed as average, which necessitates consideration of the needs of users with basic technology skills when developing digital solutions, such as interfaces for shared transport.

In developing and implementing the car sharing programmed in Adzhamka, it is possible to utilize the experience of car sharing in rural Sweden. Firstly, let's consider that electric vehicles are increasingly viewed as a promising solution for car sharing in rural areas, contributing to environmental sustainability. Furthermore, unlike cities with developed public transport systems, car sharing in rural areas will also serve as a primary alternative to private cars, particularly for those with limited access to personal transport. Innovative approaches are often required to successfully implement transport sharing in rural areas, such as localized, community-oriented service models that address the specific needs of residents. Accordingly, to begin with, the fleet will consist of 4 electric cars and 15 electric bicycles.

The public transport sharing programme in Adzhamka is a multifaceted initiative aimed at improving residents' mobility, supporting the community's economic activity, and addressing important social and environmental issues. The implementation of this model, which combines the use of electric vehicles and electric bicycles, aligns with current trends in sustainable development and offers an alternative to traditional modes of transport. By integrating electric vehicles and electric bikes, the programme responds to global trends in sustainable development, providing a modern alternative to conventional forms of transport.

At the initial stage of implementation, the programme requires an investment of 2,600,000 UAH, of which 2,000,000 UAH will be allocated for purchasing four electric vehicles and 600,000 UAH for acquiring fifteen electric bicycles. Thanks to the chosen cooperative funding model, which incorporates initial and annual contributions from the cooperative members, payment for the use of electric vehicles (30 UAH/hour for cooperative members and 50 UAH/hour for all others) and electric bicycles (10 UAH/hour and 30 UAH/hour respectively), as well as sponsorship contributions from business entities in the Adzhamka community, the programme is financially sustainable. The car sharing programme entails the creation of a cooperative with a "Roundtrip station-based" model, to be funded through initial and annual contributions from members (2,000 UAH and 1,200 UAH, respectively), sponsorship support (200,000 UAH per year), and rental fees for members (30 UAH/hour for cars, 10 UAH/hour for bicycles) and non-members, including tourists (50 UAH/hour for bicycles). Modern digital platforms, such as GoGet Carshare or RENTHUB, are advisable for managing the service.

The social significance of the programme lies in ensuring transport accessibility for a wide range of residents, including internally displaced persons, facilitating their integration and easing access to employment, medical facilities, shops, and other essential services in the regional center. Furthermore, the development of green tourism and internal mobility within the community is actively supported by the availability of electric bicycles at an affordable price for cooperative members and the ability for tourists to rent them, which serves as an additional source of income.

From an environmental perspective, the programme contributes significantly to reducing harmful emissions into the atmosphere, decreasing noise pollution, and promoting responsible resource consumption. Recognizing the limitations of the initial fleet to meet the needs of all 1200 cooperative members, a strategic direction for development is the gradual expansion of the number of available vehicles, which requires time and effective financial planning, supported, in particular, by income from vehicle rentals by cooperative members and tourist bicycle rentals, to achieve an optimal level of service and ensure the long-term stability of the programme. Furthermore, assistance from the Adzhamka rural territorial community is also appropriate.

Considering the need to ensure convenience for all members of the cooperative, particularly elderly individuals, it is advisable to utilize the digital platform GoGet Carshare, which website emphasizes the service's ease of use for older people, and RENTHUB, which is notable for offering various booking methods, including direct contact, which may be convenient for users who find it difficult to use mobile applications.

Introducing the car sharing programme will help reduce carbon dioxide emissions. Four electric vehicles operated by the cooperative travel approximately 144,000 kilometers per year (3,000 km per month each), while the average CO_2 emission figure for new passenger cars in Ukraine stands at 95 grams per kilometer. To determine how much emissions have been prevented thanks to the use of electric vehicles, it is possible to multiply the total annual mileage by the average emissions figure for petrol cars: 144,000 km multiplied by 95 g/km equals 13,680,000 grams of CO_2 (13.680 kilograms of CO_2 or 13.68 tons of CO_2). Electric vehicles do not produce direct carbon dioxide emissions during their operation. Therefore, using electric vehicles instead of internal combustion engine cars reduces the amount of harmful emissions in the atmosphere by this amount. It is important to note that CO_2 emissions may be related to electricity production, but are significantly lower than direct emissions from petrol cars. Reducing CO_2 emissions by 13.68 tons per year is crucial for improving the environmental situation in Adzhamka and beyond, as carbon dioxide is one of the leading greenhouse gases contributing to climate change. Reducing its emissions helps to slow the global warming process, lowers the risks of extreme weather events, and improves air quality for the local community. Thus, the car-sharing programme not only provides convenient and accessible transport for residents but also makes a significant contribution to environmental preservation.

There is a sufficiently high economic effect from implementing the transport sharing programme for cooperative members compared to owning a personal car and travelling by bus for residents of Adzhamka who work in Kropyvnytskyi.

For a resident who travels daily (5 days a week) to work in Kropyvnytskyi in their car, this saving may exceed 20,000 UAH per year, whereas using the bus could save more than 30000 UAH (**Table 7.3**).

Table 7.3 Calculation of the economic effect from the implementation of the koshering programme in Adzhamka for co-operative members (per year)*

No.	Traditional method of transport	Koshering	Economic Effect
1	Main expenses when using a personal car. Fuel: 230 UAH (114.66 UAH one way). For five working days a week, this will amount to 1,150 UAH, and for a year (approximately 52 working weeks) – 59,800 UAH	**Electric vehicle:** Rental cost: 30 UAH/hour. The average total rental time for a trip is 4 hours. Cost per day: 30 · 4 = 120 UAH. Cost per week (5 days): 120 UAH · 5 = 600 UAH. Cost per year: 600 UAH · 52 = 31,200 UAH. Plus annual membership fee: 1,200 UAH. The total cost of using the electric vehicle car sharing per year is 32,400 UAH	For the car owner. In the case of using an electric vehicle: 59,800 UAH – – 32,400 UAH = = 27,400 UAH. In the case of using an electric bicycle: 59,800 UAH – – 16,800 UAH = = 43,000 UAH
2	The cost of travel both ways (average value 78 UAH + 110 UAH = = 188 UAH / 2 = = 94 UAH one way): 94 UAH · 2 = 188 UAH per day. For five working days a week: 188 UAH · 5 = 940 UAH; for a year (52 weeks): 940 UAH · 52 = = 48,880 UAH	**Electric bicycle:** Rental cost: 10 UAH/hour. The average round-trip time is 6 hours. Daily cost: 10 UAH · 6 = 60 UAH. Weekly cost (5 days): 60 UAH · 5 = 300 UAH. Annual cost: 300 UAH · 52 = 15,600 UAH. Plus annual membership fee: 1,200 UAH. The annual cost of using the electric bicycle from car-sharing is 16,800 UAH	Instead of public transport: 48,880 UAH – – 16,800 UAH = = 32,080 UAH

*Note: * the distance from Adzhamka to Kropyvnytskyi is approximately 24 km.*
Source: calculated by the authors

The car-sharing programme in Adzhamka has significant economic potential for residents who regularly travel to Kropyvnytskyi, especially compared to the costs of maintaining a private vehicle. Even compared to using a bus, car sharing may be a more advantageous option for cooperative members, particularly considering the convenience and flexibility of using their transport. Implementing this programme will enhance mobility, ensure access to services, and support volunteering, economically stimulating local activity and savings for residents, while reducing emissions and noise pollution. An expansion of the fleet is planned through profits and investments. The car sharing programme holds substantial potential for community development, providing a modern, accessible, and environmentally friendly mode of transport, thus contributing to its social and economic prosperity. Additional aspects include social benefits for various population groups, stimulation of the local economy, environmental responsibility, development of charging station infrastructure, scalability, and the importance of interaction with local authorities.

7.4 Conclusions

The results of the conducted research have confirmed that models of shared transport can serve as an effective tool for implementing the CE principles at a local level. Sharing models not only ensures optimal use of material resources but also contributes to the formation of a new culture of consumption that aligns with the SDGs, specifically Goals 11 (sustainable cities and communities), 12 (responsible consumption and production), and 13 (combating climate change).

Calculations made using the example of the Adzhamka territorial community have confirmed the feasibility of implementing local shared transport programmes in rural areas, provided there is an adequate level of digital accessibility, organizational support, and cooperative management. The calculations of the environmental effect have demonstrated the potential for reducing CO_2 emissions by over 13 tons per year. At the same time, the economic assessment indicated possible annual savings ranging from 27,000 to 43,000 UAH for each user compared to alternative mobility options. The social significance of the initiative is manifested in the increased mobility of vulnerable population groups, including internally displaced persons, and in promoting the development of the green economy and rural tourism.

The results indicate that the hypotheses in the study can be considered confirmed. In particular, hypothesis H_1 regarding the potential for shared transport as an effective tool for implementing the CE principles is supported by the identified ecological, economic, and social effects. Hypothesis H_2 concerning the critical role of digital competencies and infrastructure has also been validated in the context of the Adzhamka territorial community, where the level of digital readiness significantly influences the ability to participate in the programme. Hypothesis H_3 regarding the viability of the cooperative management model has proven justified from both financial and organizational perspectives, contingent upon the involvement of local stakeholders and support from the community.

At the same time, the research findings confirm the limited scalability of such models without considering the local context. In particular, key barriers include uneven access to digital infrastructure, low levels of digital literacy in rural areas, limited community participation in decision-making, and weak institutional support. It is consistent with the conclusions of earlier studies, which emphasized the dependency of SE effectiveness on social capital, digital competencies, and technological integration levels [25].

The sustainability of shared mobility models remains a contentious issue in the long term, particularly in conditions of economic instability or institutional uncertainty. As international cases demonstrate, car sharing often proves economically vulnerable and has a high rate of company operational cessation. Consequently, an important area for further research is the examination of the financial viability of such models under cooperative or public-private management forms, as well as the development of sustainability indicators for local SE initiatives.

Future research should be focused on several directions. Firstly, it is essential to deepen the empirical foundation by studying other rural communities with varying socio-economic development levels to identify the determinants of successful sharing models. Secondly, conducting sociological research on the perception of shared mobility among different population groups is pertinent, particularly considering age, income, education level, and digital literacy. Thirdly, analyzing the possibilities of integrating "smart mobility" elements and renewable energy sources within shared transport programmes appears promising. A specific research vector should be directed towards assessing the impact of car sharing on employment, entrepreneurship development, and social cohesion in post-war rural communities.

Thus, the proposed calculation of economic feasibility allows not only for the assessment of the current potential of SE as a CE tool but also lays the groundwork for the development of new policies aimed at transforming consumption models, strengthening local economies, and achieving comprehensive sustainable development outcomes.

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CHAPTER 8

Organizational and structural modeling of the integration of marine robotics into multilevel environmental and ecological monitoring systems

Tetiana Cherniavska
Viktor Nadtochii
Anatolii Nadtochyi
Dmytro Lomonosov
Robert Cieślak
Bohdan Cherniavskyi

Abstract

The section explores the basic theoretical and methodological principles of forming an organizational model for using marine robotics (MRO) as a tool for implementing systematic and scientifically sound environmental monitoring of the marine environment. Considering new challenges associated with large-scale environmental threats, military operations and increased anthropogenic load, special attention is paid to the development of conceptual approaches that allow for flexibility, sustainability and efficiency of the organizational structure. The focus of the analysis is a combination of a systems approach, engineering cybernetics, ecological systemology and the theory of management of complex socio-technical systems. A list of key principles for building an organizational model is proposed, which covers aspects of goal orientation, adaptability to dynamic external conditions, integration with national and international systems, technological compatibility, security, resource efficiency and transparency. Each of the investigated principles is formalized in the form of a mathematical organizational model, which forms the basis for the subsequent modeling of the functioning of the system in conditions of a dynamically changing environment, including, among other things, scenarios of post-conflict recovery and water resources remediation. Such an approach not only ensures the scientific validity of the construction of the organizational model but also provides tools for practical analysis of the effectiveness of its functioning, support for management decision-making, as well as optimization of interaction between all participants of the environmental monitoring system and risk management.

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The systematization of the obtained results becomes a key stage in the creation of an integrated management system of robotic platforms for the purposes of environmental and ecological monitoring and water resources remediation. Such a system is capable of scaling, adapting to various tasks and being integrated into the environmental policy of Ukraine, especially in conditions of post-conflict recovery and sustainable development.

Keywords

Marine robotics, autonomous systems, environmental and ecological monitoring, organizational model, adaptability, mathematical modeling, multilevel governance, resource efficiency, ecosystem sustainability, remediation.

8.1 Introduction

In the 21st century, the rapid growth of environmental challenges in the marine environment, in the context of military operations, man-made disasters and climate change, creates an urgent need to develop new approaches to environmental monitoring. Marine robotics (MRO) is considered by the scientific community as a promising tool in solving environmental control problems, due to its ability to operate autonomously, high maneuverability and adaptability in complex environments. However, the effective integration of MRO into the environmental monitoring system requires not only technical improvement, but also a scientifically sound organizational model that would ensure the coordinated functioning of socio-technical components within a multi-level management structure [1].

The scientific principles of forming such models are explored in the works of a few leading scientists. In particular, the methodological foundations of ecological robotics and complex adaptive systems are highlighted in the works of K. Rajan et al. and J. B. J. Harvey et al., which emphasize the importance of autonomous marine vehicles in sustainable development strategies [2, 3]. Hierarchical structures of robotic systems control under uncertainty with the issues of integrating MRO into national and transboundary monitoring systems are analyzed and considered in the studies of E. Fiorelli et al. [4]. In Ukraine, the issues of creating technological platforms for monitoring water areas using unmanned vehicles were raised in the works of V. Blintsov, G. Babkin [5], B. Gordeev, I. Sabutsky, A. Nadtochyi, V. Nadtochii, A. Burunin, O. Zbrutskyi, and others [6–9].

Despite the existing scientific developments, key issues related to the holistic organization of the functioning of marine robotics within the framework of environmental management systems remain unresolved. In particular, the problem of formalizing the structure of interaction between management levels (national, regional, operational), integrating marine robotics into legal, logistical and informational contexts, ensuring adaptability in crisis situations, as well as harmonizing national models with international standards and platforms, is relevant. The lack of a single structural and functional model that combines technical, institutional and strategic components hinders the widespread introduction of marine robotics into the practice of environmental monitoring.

The aim of this research is the development of the theoretical and methodological basis of the organizational and structural model of integration of marine robotics into multilevel systems of environmental and ecological monitoring and water resources remediation. Special attention is paid to ensuring efficiency, adaptability, resource justification, and resilience to external threats, considering the specifics of post-conflict recovery and the priorities of Ukraine's environmental policy in the context of European integration [10].

8.2 Systemic basis for forming an organizational model for using marine robotics for environmental and ecological monitoring

In the current conditions of increasing environmental threats in marine areas, caused by both natural and anthropogenic factors (in particular, the consequences of military actions, man-made accidents, and climate change), there is an objective need to create innovative organizational models that can ensure the effective, operational and safe functioning of marine environmental monitoring systems. MRO tools have significant potential in this area, but their implementation remains fragmented, technologically isolated and poorly integrated into the general structures of environmental management [11].

The main scientific problem is the need to develop a systemic basis for an organizational model that would consider the complexity and multicomponent nature of the socio-technical monitoring system, ensure its adaptability to crisis conditions, the ability to self-organize, as well as sustainable functioning in conditions of uncertainty, risks and limited resources. The lack of a formalized understanding of the interaction of structural levels, information flows, technical platforms and institutional participants limits the possibilities of practical implementation of MRO at the level of state or transboundary environmental policy.

Solving this problem requires the scientific substantiation of an open, hierarchically organized, cybernetically managed, and normatively integrated system that combines methodologies of systems analysis, management theory, ecological systemology, and crisis administration to create new generation organizational architecture in the field of marine monitoring [12].

The formation of an effective organizational model for the use of MRO is impossible without a clear definition of its systemic basis – a theoretical framework that allows for a comprehensive description of the structure, functioning, relationships and adaptability of the organizational system in a dynamic environment. In this context, the organizational model is considered as an open adaptive socio-technical system that integrates with:

– human components (operators, analysts, administrators) that provide task setting, decision making, and data interpretation;

– technical elements (unmanned aerial vehicles, sensors, service hubs) that implement the functions of collecting, transmitting and processing information;

– institutional mechanisms (legislation, protocols, standards) that formalize the interaction of participants;

– ecosystem factors (hydrology, climate, consequences of hostilities) that create the environment in which the system operates.

The system basis of the model is based on a combination of scientific approaches that ensure its integrity, adaptability, and functionality in the conditions of a complex marine environment (**Table 8.1**).

These approaches together form a scientifically sound, adaptive and effective organizational model that meets the challenges of modern marine environmental monitoring.

The system framework provides the ability to model the organizational model of the MRO as a complex, living, capable of development structure, which combines technological solutions, institutional mechanisms, ethical constraints, and a strategic vision of sustainable development.

Within this system paradigm, MROs are considered as autonomous sensor-control units capable of interacting both with each other and with other elements of ecosystem management (monitoring centers, analytical hubs, international platforms, etc.). The organizational system must provide feedback, adaptation to changing conditions (weather, man-made, political), as well as resistance to risks (military, logistical, information).

The model is based on the idea of a digital complex multi-level hierarchical structure, covering strategic (national), regional and operational levels of management. Such a structure allows for both centralized decision-making and local flexibility in responding to specific challenges. Each level of the system has a specific functional specialization: strategic planning, coordination of operations, data processing, operation of weapons and ammunition, maintenance and logistics [12, 13]. The system framework assumes a multi-level hierarchy, where each level performs specific functions and has defined boundaries of responsibility (**Table 8.2**, **Fig. 8.1**).

Table 8.1 Scientific approaches to the system basis of the marine robotics model for environmental and ecological monitoring

Approach	Description
Systemic approach	Allows to consider the model as a holistic integrated system in which technical, informational and organizational elements interact. Ensures consistency between subsystems: MRO, environmental data, logistics, management and feedback
Cyber-physical approach	Provides a combination of physical processes (actions of the MRO in the environment) with digital components (sensors, computing, communication). Allows for real-time operation due to constant exchange between environmental objects and analytical platforms
Hierarchical approach	Defines a three-level management structure: central, regional, and operational levels. Provides for the distribution of powers, responsibilities, areas of action and forms of interaction between levels
Process approach	Focused on describing and optimizing the sequence of actions within environmental missions. Allows modeling of tasks, resources, information, and operational management flows to ensure continuous operation
Situational approach	Provides for flexible adaptation of system actions depending on environmental conditions, threat level, or new goals. Used to generate response options in the mode of unpredictability or instability
Synergistic approach	Helps achieve a mutual reinforcement effect between system elements – when the interaction of robotic tools, operators, analytical units and management structures increases the overall efficiency of the system compared to the isolated functioning of its parts

Table 8.2 Multi-level hierarchical management structure of the model for the use of marine robotics for environmental and ecological monitoring

Level	Function
Central (national)	Strategic planning, financing, and integration with international structures
Regional	Coordination of field missions, logistics, data processing, and personnel training
Operative	Direct operation of the MRO, data collection and transmission, maintenance

The central (national) level of management plays a key role in shaping the strategy of functioning and development of the organizational model of using marine robotics for environmental and ecological monitoring. It is at this level that the national policy in the field of environmental monitoring of the marine environment is determined, priorities, goals and directions for integrating MRO into the national ecological security system are formulated, considering current and projected threats, including the consequences of military actions, climate change and man-made factors.

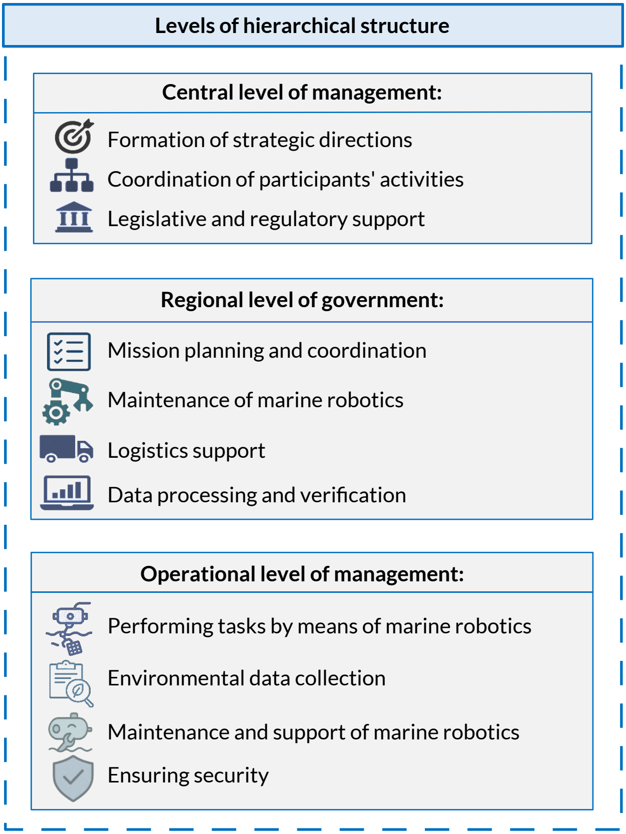

Fig. 8.1 Levels of the hierarchical structure of the management model for the use of marine robotics for environmental and ecological monitoring

One of the fundamental functions of the central level is the development of the regulatory framework, technical regulations, procedures for interagency cooperation and standards for the collection, processing and use of environmental information. It is also here that strategic planning of the institutional environment takes place: the creation and regulation of the activities of state marine and environmental management centers, technical hubs, analytical laboratories, training centers, as well as the coordination of participation in international marine and environmental programs.

Financial planning and system support are carried out at the central level: determining the volume of budget funding, developing state target programs, distributing financial resources between regional levels, and seeking international donor support. An important component is ensuring digital infrastructure and cybersecurity: from establishing data protection protocols to implementing cloud platforms and satellite monitoring, considering interoperability requirements with international information systems. The central level is also responsible for international coordination, representing Ukraine in global and regional initiatives on maritime safety and environmental protection, ensuring the harmonization of Ukrainian environmental protocols with the norms of international maritime and environmental law, and coordinating cross-border actions within the framework of technical assistance or operational response projects. In addition, the national level provides system analytics, forecasting changes in the marine environment, assessing the effectiveness of the MRO operation, forming quality indicators, and recommendations for updating software and technical components of the system, as well as developing scenarios for scaling the system in accordance with future challenges [14, 15]. This level is a consolidating core and performs the function of strategic management of the entire hierarchy of the organizational model.

The regional level is a critically important component of the management hierarchy, since it is at this level that the strategy formulated by the central authorities is practically implemented, considering the specific geographical, ecological, technogenic and social context of each marine region. Its main task is to ensure operational coordination, technical management, logistical support and initial analytical processing of data obtained from marine robotics within a defined water area or coastal zone. The functions of the regional level include the organization and control of the implementation of environmental monitoring missions in accordance with the plans approved by the national centers. Within the framework of this task, regional units form schedules for the deployment of environmental monitoring missions, determine observation areas, and adjust mission routes considering local weather conditions, hydrological conditions or identified threats. They also coordinate with related agencies: the Sea Ports Administration, the State Emergency Service of Ukraine, the Environmental Inspectorate and municipal services involved in the implementation of local environmental protection measures.

At the regional level, MRO maintenance is carried out, including preparation, charging, calibration of sensors, software updates, scheduled and emergency repairs.

For this purpose, technical hubs are created – service centers with appropriate equipment, spare parts, test pools and qualified personnel. A separate role is played by the logistics function: ensuring the smooth operation of missions requires the availability of vehicles, support vessels, ground infrastructure for communications, communication channels, points of maintenance and storage of weapons. Regional centers are responsible for monitoring resources, managing personnel and coordinating responses in case of unforeseen situations. In addition, it is at the regional level that the primary processing and verification of data received from robotic platforms is concentrated. The data undergoes primary quality control, pre-processing, georeferencing, and visualization and is transmitted to the central level or scientific and analytical centers for deeper analysis. Part of the data can be used at the local level for operational decision-making regarding local environmental incidents, identification of pollution sources, and formation of emergency response protocols.

Regional structures also play an important role in training and certifying personnel, including MRO operators, data analysis specialists, and technical personnel. In cooperation with higher education institutions and scientific institutions, regions can act as basis for conducting study missions, training, internships, and testing innovative solutions. The regional level acts as the operational and technical core of the system, ensuring the transformation of strategic decisions into practical actions, connecting national policy with specific environmental objectives in coastal and marine zones. It creates the prerequisites for the continuity of the system's functioning, its flexibility, territorial differentiation and the ability to respond quickly.

The operational level is the basic and at the same time critically important link in the hierarchical structure of the organizational model for the use of marine robotics for environmental and ecological monitoring. It is at this level that the direct implementation of field tasks takes place: deployment, operation, maintenance and feedback of robotics with the physical environment. The operational level provides daily, routine, but technically complex activities that are the basis of the entire environmental monitoring system.

Operational level functions are focused on the execution of missions by means of MRO, which involves preparing the vehicles for launch, performing navigation, following the specified routes, activating the relevant sensor systems and ensuring the stable collection of environmental data. Operators perform these tasks according to instructions and technical scenarios received from regional or central control centers, adapting them in real time to specific conditions on the ground: hydrological, weather, technical or security. At the operational level, a primary ecosystem picture of the monitoring area is formed: indicators of water quality, depth, presence of pollution, remains of military equipment, explosive objects, biological markers, noise signatures, etc., are recorded. The collected data is transmitted via ground stations or satellite channels to the regional center. In case of detection of critical situations (oil spills, mass death of marine organisms, detection of explosive objects), the operational level initiates a direct emergency information channel.

Another important function of this level is the maintenance and daily maintenance of the technical condition of the missile defense system. This includes charging batteries, calibrating sensors, checking hydraulic and navigation systems, identifying and eliminating faults, updating on-board software, and checking the tightness of the hulls [15]. Such maintenance is carried out either in the field (on vessels or in mobile stations) or within the framework of stationary technical support points.

The operational level is also responsible for the safety of operations, both in a technical, environmental and legal sense. MRO must operate within authorized zones, comply with international maritime law, and not pose a threat to maritime transport, fisheries or natural habitats. In war or post-conflict situations, this level also faces the risks of mine hazards, radiation or chemical contamination.

In addition to the technical component, the operational level also includes the human factor: a team of operators, technicians, and junior specialists who operate in the field. Their interaction is based on strict adherence to protocols, equipment skills, and the ability to respond quickly to non-standard situations.

The operational level is the "final link" of the system, which translates strategic decisions and plans into concrete actions in the real environment. The accuracy of environmental assessments, the speed of response to threats, and the overall effectiveness of the organizational model in the field of marine monitoring depend on its coordinated work.

The transformation from a hierarchical structure to an organizational model in the field of marine robotics for environmental purposes reflects the evolution of the management system, from a rigidly defined division of functions to a holistic, flexible mechanism for coordinating the interaction of all involved elements.

The hierarchical structure sets a framework in which each level (central, regional, operational) performs specific functions: from strategic planning to direct task execution. However, in the complex, dynamic maritime environment, this is not enough.

The organizational model details the ways of interaction between levels, considers information flows, physical actions and management decisions, combined into contours. It provides not only vertical commands, but also horizontal connections, allows for quick response to changes, and integrates technical, information and analytical elements into a single functional space. Such a model provides a balance between centralized control and local autonomy, between algorithmic solutions and adaptive behavior of technical means. It is the basis for the implementation of intelligent technologies for controlling marine robotic systems, capable of effectively operating in the field of environmental monitoring and protection of the aquatic environment.

The organizational model is a dynamic, adaptive and managed system that interacts with the external environment through three main circuits: physical (impact and effects on the ecosystem), information (data collection, processing, transmission) and management (goal formation, decision-making, response to changing situations). These circuits ensure the continuity of the system's functioning even under conditions of instability – in the event of failures, emergencies or changes in the political or environmental context (**Fig. 8.2**).

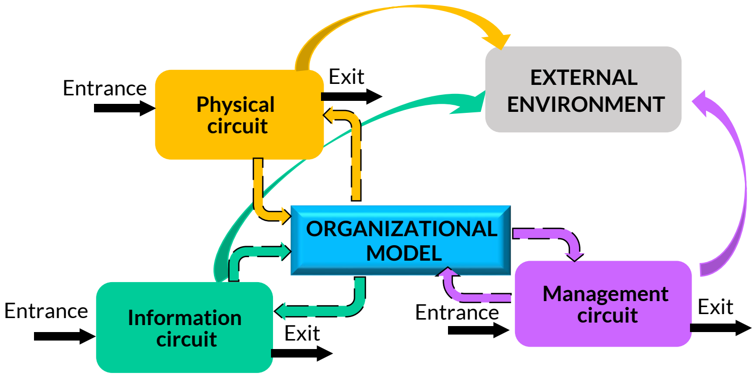

Fig. 8.2 Organizational model of using marine robotics for environmental and ecological monitoring

An analytical representation of the input and output elements of each of the three contours of the organizational model, formed based on **Fig. 8.2**, is presented in **Table 8.3**.

Information interaction in the system has a vertical and horizontal nature: data is transmitted from the MRO to regional and central hubs, and from there – back in the form of control signals, missions or action scenarios. In parallel, horizontal exchange between elements at the same level operates – for coordination of decisions, clarification of data, operational duplication or backup.

The central element of the system framework is the functional goals, which describe the desired results of the system's activities in quantitative and qualitative form: coverage of water areas by monitoring, accurate and speed of threat detection, resource efficiency, and compliance with international standards. This function is a key parameter for optimizing the model architecture, action algorithms, and strategic management.

Table 8.3 Analytical representation of input and output elements of the contours of the organizational model of the use of marine robotics for environmental and ecological monitoring

Contour	Essence	Input elements	Output elements
Physical circuit	The influence and interaction of the organizational model with the natural environment	Hydrometeorological conditions (temperature, waves, currents)	MRO impact on the marine environment (e.g. cleanup, contamination containment)
		Level of water pollution (chemical, biological indicators)	Change in ecosystem parameters due to system actions
		Presence of explosive objects or man-made remains	Environmental modification (interventions, demining, biomonitoring)
		Morphological characteristics of the water area (depth, bottom relief)	Digital signals from technical means, spatio-temporal coordinates of actions
Information circuit	Processing and transmission of environmental, technical and situational information	Telemetry, sensor data from robotic platforms	Analytical reports, maps, risk assessments
		Satellite and sonar images	Data transmitted to control centers
		Signals about malfunctions, risks, and incidents	Interpreted signals for decision making
		External information flows (forecasts, regulatory restrictions	Information support for strategic planning
Management circuit	Goal formation, decision making and regulation of system behavior	Results of information analysis	Planned MRO missions (routes, modes, tasks)
		Political, legal and environmental requirements	Emergency protocols
		Real-time situation assessment	Management decisions: reallocation of resources, adjustment of strategy
		Strategic goals or objectives from the government, international structures	Updated adaptation goals and scenarios

The system also has the properties of learning and self-improvement through data accumulation, analysis of previous missions, implementation of machine learning, and predictive models of changes in the ecological state. It is capable not only of reacting, but also of proactively forming scenarios of the development of events.

8.3 Principles of organizational model formation

The formation of an organizational model for the use of MRO for the purposes of environmental and ecological monitoring is based on a combination of the principles of organizational management theory, ecological systemology, engineering cybernetics, and the theory of complex socio-technical systems. In modern conditions considering the consequences of the war in Ukraine, there is a growing need to build adaptive and sustainable organizational models capable of ensuring sustainable monitoring of the marine environment based on the latest technologies [16].

The basis of the model is a structural-functional approach, which allows reflecting the logic of the relationship between entities (scientific institutions, operators, environmental services, international partners) and technical components (unmanned marine vehicles, control stations, service hubs, analytical platforms, etc.).

Within this approach, the organizational model should provide:

– institutionalization of powers and a clear division of functions between interested structures;

– integration of research and applied activities on the development and improvement of marine robotic platforms;

– ensuring sustainable information exchange between field operators, scientific centers and management bodies;

– adaptation to the ecological dynamics of marine areas, considering the consequences of military operations, pollution, changes in the hydrological regime, etc.;

– optimization of resource provision, including human, material, financial and information resources.

The formation of an effective organizational model for the use of MRO should be based on several key principles that ensure its scientific validity, systemic integrity, adaptability to crisis conditions, and orientation towards the sustainable development of marine ecosystems.

Table 8.4 presents the main principles, considering wartime conditions and reconstruction needs.

Table 8.4 Principles of the methodological basis of the model for the use of marine robotics

Principle	Description
Goal-oriented	The organizational structure should be aimed at achieving specific goals: preventing environmental disasters, detecting pollution, monitoring the state of the marine environment, and assessing the consequences of hostilities for marine ecosystems. In focus: monitoring water areas, in particular in ports, river mouths, areas with the probable presence of explosive objects
Adaptability and crisis resilience	The model should consider unforeseen risks, including military threats, cyber incidents, and logistical disruptions. It should be flexible to allow for rapid reorientation of resources in the event of emergencies or changes in the political context
Integrations	Marine robotics equipment should be organically integrated into the national environmental monitoring system, interact with other environmental, defense and research structures, as well as with international partners. Integration includes data exchange, protocol coordination, joint missions
Hierarchies	The structure should ensure a clear division of functions between central, regional and executive elements. The hierarchy should identify key coordinators (state agencies, command centers) and executors (operational teams, operators, service departments)
Scientific validity	The construction should be based on system analysis, the use of modern methods of environmental forecasting, digital modeling, GIS-technologies and machine learning for automated processing of MRO data
Technological compatibility and standardization	The use of robotic systems should involve the unification of interfaces, data transfer protocols, and interaction algorithms, which allows for easy integration of new platforms, sensors, and equipment from different manufacturers
Security and ethical responsibility	The MRO operation must comply with the requirements of environmental safety, international maritime law and humanitarian law in terms of preventing negative impacts on the environment or interference with the sovereignty of territories. In wartime, it is especially important to consider the dual (civilian-military) use of technologies
Openness and cooperation	The organizational model should facilitate transparent data exchange with the scientific community, public organizations, and environmental initiatives. Cooperation with foreign partners allows not only strengthen potential, but also to accelerate the implementation of new developments
Resource efficiency	Rational use of financial, human and technical resources should be based on assessing the effectiveness of operations, optimizing MRO routes, and forecasting maintenance and logistics needs
Continuity	The system for organizing the MRO operation must function on a permanent basis, regardless of changes in the political or military situation. Continuity is ensured by resource redundancy, system autonomy, and highly qualified personnel

The principle of goal orientation implies that the entire structural and functional model of the use of marine robotics should be aimed at achieving clearly defined environmental, safety and socially significant results. This means that the functioning of each element of the system, from the central management body to the direct executor at the operational level, should be subordinated to the implementation of a specific goal. This approach avoids the dispersion of resources and ensures consistency of actions at all levels. Goals set the functional logic of the system, determine which technologies, types of devices and sensors should be involved, how missions and response algorithms are formed, how resources are distributed, and what information is a priority for collection and analysis. In crisis conditions, the ability of the model to switch between long-term strategic guidelines, medium-term tasks and operational goals is of particular importance. It is goal orientation that provides the model with direction, development logic and clear measurability of effectiveness. It allows ensuring that the work of the MRO meets the real needs of environmental security, humanitarian response, and international cooperation.

The next principle of the methodological basis of the model for using marine robotics is the principle of adaptability and crisis resistance.

The principle of adaptability and crisis resilience is key to building a structural and functional model for the use of MRO in conditions of high dynamism and uncertainty of the external environment. It determines the ability of the system not only to perform functions in standard conditions, but also to ensure its viability, efficiency and recovery during crisis events, in particular – military operations, man-made disasters, sudden changes in climatic and hydrological characteristics.

This principle implies that the organizational model should be able to change the configuration of its structure, mission routes, interaction algorithms, resource allocation priorities, and chains of command in accordance with changing external circumstances. Adaptability is manifested in the ability to scale up or down individual system components, reconfigure the MRO software in real time, reassign functions between management levels, and change decision-making logic based on new data.

In practical terms, this principle is implemented through flexible system architecture, the availability of adaptive software modules, mobile technical hubs, an extensive data reception/transmission network, and a system of operational duplication of critical functions. Its implementation is a prerequisite for the long-term stability, reliability, and efficiency of marine robotics as an environmental response tool in the 21st century.

The principle of integration is no less important than other principles in the methodological basis of the model for the use of marine robotics.

The principle of integration in the model of using MRO for environmental and ecological monitoring means building a system in which all elements: technical, informational, organizational and functional – are interconnected, interact based on a single logic and complement each other to achieve a common goal. Integration ensures the integrity of the system, its ability to comprehensively act, interagency cooperation, technology compatibility and continuous data exchange.

The principle of integration is the foundation for building an effective, controllable and adaptive system in which marine robotics plays the role not of an isolated tool, but of an active element in an interacting network of decisions, actions and responsibilities. It ensures consistency, coherence and efficiency in the implementation of environmental protection and crisis missions in the complex conditions of the marine environment [17, 18].

The principle of hierarchy in the model of using MRO for environmental and ecological monitoring means building a multi-level management system in which functions, powers, responsibilities, and information flows are clearly distributed between levels – from strategic (central/national) to operational (MRO missions in the field).

This principle allows for the effective functioning of the system due to:

– consistency of goals between levels;

– effective delegation of tasks;

– stable management in difficult situations;

– adaptation and localization of solutions according to the specifics of the region or task.

The principle of hierarchy is based on the idea of centralized strategic planning with the simultaneous ability to decentralize response. This allows maintaining a balance between formativeness, predictability of actions and flexibility in the field. The central level is responsible for policy, standards, strategic financing, goal setting and coordination of national and international efforts. The regional level adapts the policy to the specifics of specific water areas, organizes inter-institutional interaction and coordinates local resources. The operational level carries out the missions of the MRO, exercises direct control over technical means, conducts environmental monitoring and ensures the implementation of instructions received from above [19, 20].

The principle of scientific validity in the model of using MRO for environmental and ecological monitoring implies that all management, engineering, technological and organizational decisions should be based on the results of scientific research, proven theoretical concepts and empirical data. This principle ensures that the MRO system is not a random or situational entity, but is based on systemic analysis, interdisciplinary knowledge and scientific logic, which increases its effectiveness, accuracy and long-term viability.

Scientific validity requires the integration of knowledge from the following key areas: hydro ecology, oceanography, information technology, artificial intelligence, mechatronics, system management, environmental safety, and the regulatory framework for maritime activities. This means that the planning of MRO missions, decision-making algorithms, sensor locations, survey routes, and data processing methods must be designed based on models that consider environmental patterns, risks, process dynamics, and predictive scenarios.

The principle of scientific validity is the key not only to the effective functioning of MROs, but also to their sustainable integration into the environmental safety management system. It ensures the transition from reactive to proactive management, where decisions are made not after the fact, but based on the analysis of trends, models and scenarios confirmed by scientific data.

The principle of technological compatibility and standardization is key to the effective integration of MRO tools into complex systems for environmental monitoring, humanitarian demining of water areas, and emergency response. This principle ensures the coordinated operation of heterogeneous technical tools, information systems, control protocols, and communications within one or more organizational and technical structures.

Technological interoperability implies the ability of MROs, both autonomous and manned, to operate in an interconnected environment, where devices of different types (surface, underwater, airborne), from different manufacturers, with different software platforms, can exchange data, coordinate actions and ensure continuity of operation in real time. This is achieved through the unification of interfaces, the use of open data exchange protocols, and compliance with international or national standards (e.g., IEEE, ISO, NATO STANAG, ITU) [19, 20].

Ultimately, the principle of technological interoperability and standardization is not just an engineering convention, but a strategic prerequisite for creating a sustainable, scalable, safe, and efficient marine robotics system capable of meeting the challenges of environmental security in the 21st century. Its implementation guarantees the integrity of the infrastructure, flexibility of development, responsiveness, and quality of data for decision-making.

The principle of safety and ethical responsibility in the use of marine robotics for environmental and nature protection monitoring is a system-forming element that defines the permissible limits of design, implementation and operation of such technologies. Its content is to ensure technical, informational, environmental and social safety while minimizing risks to people, the environment, infrastructure, as well as adhering to the principles of humanism, transparency, inclusiveness and legal responsibility [19, 20].

The operation of marine resources in open seas or coastal ecosystems is always associated with potential threats, both man-made and biological, legal or geopolitical in nature. Ensuring security means having mechanisms for preventive risk analysis, designing reliable management systems with multi-level redundancy, compliance with international maritime and environmental law, and protecting data from interference by third parties or organizations. The issue of cybersecurity requires special attention, since most marine resources are part of network structures operating in real time.

Safety and ethical responsibility are not only a requirement for the functioning of the MRO but a holistic philosophy that ensures the legitimacy, trust, and sustainable development of marine robotics technologies in the context of environmental protection, social consent, and responsible risk management.

The principle of openness and cooperation in the model of using MRO means provides for an institutional, technological and communication orientation towards transparency of actions, intersectoral interaction and multi-level partnership as the basis for the sustainable functioning and development of environmental monitoring and environmental protection activities in the marine environment.

This principle is based on the recognition that contemporary challenges, such as the degradation of marine ecosystems, the effects of military operations, climate change or anthropogenic pressure on coastal zones, cannot be solved solely by the efforts of individual institutions or government bodies. The MRO application in such conditions requires the involvement of a wide range of stakeholders: scientific institutions, government agencies, international organizations, local governments, voluntary and community structures, commercial operators and equipment manufacturers.

Openness and collaboration not only reduce social and environmental risks but also create added value for MRO technologies, transforming them from highly specialized technical solutions into a platform for broader ecosystem management in the areas of security, science, and environmental protection.

The principle of resource efficiency in the use of MRO for environmental and ecological monitoring is a key tool for achieving a balance between technological efficiency, economic feasibility, environmental efficiency and operational sustainability. In the context of integrated marine environmental management, it defines the way in which all types of resources – material, energy, information, financial and human – are allocated, used and re-engaged to achieve maximum effect with minimal cost.

In general, the principle of resource efficiency sets not only the technical logic for building a marine robotics model, but also the strategic framework for managing all resource flows, which guarantees sustainability, economic feasibility, rapid payback, and environmental safety of the implementation of marine robotic systems in crisis and peacetime conditions.

The principle of continuity in the model of using MRO for environmental and ecological monitoring determines the ability of the system to function stably, systematically and with a guarantee of prompt recovery after external disturbances or crisis events. This principle becomes especially relevant in unstable environments, were natural, man-made or military factors can lead to the shutdown of observation systems or the loss of critical environmental information.

Continuity in the context of MRO is not only the regularity of monitoring missions, but also the ability to ensure technological, informational, personnel and institutional sustainability of the system. It is implemented through a combination of infrastructure readiness, operational reserve, backup, multi-agent management architectures and rapid response procedures.

Overall, the principle of continuity in a marine robotics system ensures that environmental monitoring is not dependent on human error, random events, or infrastructure limitations. It forms the basis for creating a reliable, self-healing, decentralized system capable of operating in the face of turbulence, climate change, environmental threats, or emergencies.

8.4 Mathematical formalized representation of principles

To create a holistic analytical basis for describing, analyzing and optimizing the functioning of the model of using marine robotics in conditions of complex and dynamic interaction of natural, technical and organizational factors, it is possible to form a mathematical representation of ten principles of forming an organizational model for environmental and ecological monitoring. This model allows to generalize the content of each principle in the form of mathematical relationships that reflect the dependencies between the key parameters of the system's functioning. This approach provides the ability to model the behavior of the system in various situations, including under conditions of uncertainty, risks and limited resources [21, 22]. Through mathematical abstraction, a basis is created for developing tools for assessing the effectiveness, adaptability and sustainability of the organizational structure, as well as for building scenarios for making management decisions based on parametric data and objective criteria. This allows to integrate marine robotics into environmental monitoring systems, considering both strategic and operational aspects of management [23–25]:

1. Mathematical representation of the principle of goal orientation. For each MRO r_i, the correspondence of the goal t_j must be determined

$$\forall r_i \in R, \exists t_j \in T: \mu\left(r_i, t_j\right) \to \max, \tag{8.1}$$

where $\mu(r_i, t_j) \in [0, 1]$ – the measure of the task's suitability; $T = \{t_1, t_2, ..., t_m\}$ – set of goals (monitoring, detection, support, etc.); $R = \{r_1, r_2, ..., r_n\}$ – the set of MRO tools.

2. Mathematical representation of the principle of adaptation. The system must remain stable under changing external conditions θ

$$\lim_{\Delta\theta \to 0} \left| \frac{\partial F}{\partial \theta} \right| < \varepsilon, \tag{8.2}$$

where ε – the permissible limit of sensitivity of the functional to changes; F – functional quality or efficiency of the entire system; θ – a set of external conditions (for example, military situation, weather conditions, regulatory restrictions).

3. Mathematical representation of the integration principle. There is a function for integrating data from various sources

$$I = \sum_{i=1}^{n} D(r_i) \cup D_{\text{other systems}} \Rightarrow \text{compatible model} \Rightarrow \text{analytics}, \tag{8.3}$$

where $D(r_i)$ – a set of data collected by robot r_i.

4. Mathematical representation of the principle of hierarchy. A hierarchical control structure S is formed as a directed graph

$$G = (S, E), \tag{8.4}$$

where E – directions of subordination, $depth(G) = d$; d – hierarchy level (usually 3: central – regional – local); $S = \{s_1, s_2, ..., s_k\}$ – a set of structural divisions (regional centers, operator stations, etc.).

5. Mathematical representation of the principle of scientific validity. For each element of the system, a model is used

$$F(r_i) = f(D(r_i), \theta, M), \tag{8.5}$$

where M – a mathematical or empirical model for assessing efficiency; $D(r_i)$ – a set of data collected by robot r_i; θ – a set of external conditions (for example, military situation, weather conditions, regulatory restrictions).

6. Mathematical representation of the principle of technological compatibility. A set of MRO R must have a common standard σ and fulfil

$$\forall r_i, r_j \in R, \text{compatibility}(r_i, r_j) \geq \alpha, \tag{8.6}$$

where $\alpha \in [0,1]$ – minimum allowable compatibility level; $R = \{r_1, r_2, ..., r_n\}$ – a set of marine robotics (MRO) tools.

7. Mathematical representation of the principle of safety and ethical responsibility. The functioning of the system must not exceed the regulatory permissible risk

$$P_{risk}(r_i) \leq P_{marginal} \forall r_i \in R, \tag{8.7}$$

$R = \{r_1, r_2, ..., r_n\}$ – a set of MRO tools.

8. Mathematical representation of the principle of openness. The level of data openness is described through the accessibility metric

$$A(D) = \frac{|D_{open}|}{|D_{all}|} \geq \delta, \tag{8.8}$$

where δ – the regulatory level of transparency; $D(r_i)$ – a set of data collected by robot r_i.

9. Mathematical representation of the principle of efficiency. Optimization model of resource minimization when achieving goals

$$\min_{x \in X} C(x) \text{ provided that } F(x) \geq F, \tag{8.9}$$

where x – the system deployment parameters; $C(x)$ – costs; F – the functional quality or efficiency of the entire system.

10. Mathematical representation of the principle of continuity. The model should have the lowest coefficient of loss of functionality during failures

$$\phi = \frac{F_{after\ malfunction}}{F_{normative}} \geq \gamma, \tag{8.10}$$

where $\gamma \in [0.7, 1.0]$ – the target level of continuity; F – the functional quality or efficiency of the entire system.

The mathematical formulation of an organizational model for the use of marine robotics for environmental and ecological monitoring is based on the combination of ten key principles in the formalized equation. The efficiency of the system at time t, denoted as $E(t)$, is determined by the weighted sum of the values of each of the principles

$$E(t) = P_1 \cdot w_1 + P_2 \cdot w_2 + \cdots + P_{10} \cdot w_{10}, \tag{8.11}$$

where $P_1, \ldots, P_{10}$ – values reflecting the degree of implementation of each of the 10 principles of the organizational model; $w_1, \ldots, w_{10}$ – weight coefficients reflecting the significance of each principle in the overall structure; $E(t)$ – the integral function of the efficiency of the organizational model over time.

This equation allows for modeling and optimizing the functioning of marine robotics systems depending on changing priorities, weighting factors, and environmental conditions. If necessary, nonlinear growth dynamics functions can be added to the model, such as logistic dependencies or exponential decay of the influence of individual factors over time.

The constructed mathematical representation of the ten principles of functioning of the organizational model of using MRO allows moving from conceptual organizational to the applied stage of modeling and simulation of the dynamic behavior of the system. In the proposed structure, the principles act not only as normative or conceptual guidelines, but also as quantitatively determined parameters that directly affect the functioning of the system in the decision space [24–26].

The mathematical description of each principle through the corresponding functions of efficiency, compatibility, risk or adaptability provides the possibility of integrating them into the target control function, which models the dynamic behavior of the system over time. This approach allows for analyzing the sensitivity of the system to changes in individual principles, assessing their mutual influence, and predicting the effectiveness of management decisions in different scenarios of the MRS operation.

At this stage, it becomes appropriate to use computer modeling tools to conduct simulations that simulate the functioning of the system under conditions of changing one or more principles. This allows not only to test hypotheses about their impact, but also to form optimal management strategies that provide a balance between adaptability, efficiency, security and other critically important characteristics of the organizational model.

A simulation of the implementation of ten key principles of the organizational model for the use of marine robotics for environmental and ecological monitoring demonstrates the dynamics of the implementation of each principle over a 12-month period. The modeling results are based on formalized mathematical dependencies that describe the weight of the influence of each principle on the overall effectiveness of the functioning of the organizational structure of the system. The simulation uses nonlinear growing functions of the logistic curve type, which consider both the initial inertia of implementation and the saturation of the effect under resource constraints and organizational interaction.

The dynamics of each principle in the graph reflect the level of its integration into the organizational model at a specific point in time. The most rapid growth is observed for the principles of flexibility, integration and risk orientation, which indicates the high priority of these factors in the current conditions of environmental uncertainty and military threats. On the contrary, the principles of stability and hierarchy have a slower implementation dynamic, which is explained by the need to adapt to changing external conditions.

Mathematical simulation also allowed to analyze the interdependencies between the principles of how increasing the efficiency of coordination contributes to the faster implementation of the principle of adaptability, or how the balance between centralization and decentralization affects the stability of the functional interaction of departments. According to the simulation results, the overall efficiency of the system reaches a peak value after 10 months of implementation, which correlates with the inertial phase of the deployment of technical resources and personnel training.

The simulation demonstrates that applying science-based principles to the design of an organizational model for marine robotic systems predictably achieves environmental monitoring goals in complex environments. This provides a theoretical and applied foundation for further scaling up the concept in a national and international context.

To analyses the functional dynamics of the organizational model of using marine robotics for environmental and ecological monitoring, a simulation was conducted based on mathematically formalized management principles.

The model considers six of the ten key principles: goal orientation (P_1), adaptability (P_2), crisis resistance (P_3), integration (P_4), hierarchy (P_5), and resource efficiency (P_{10}).

Each of the principles is presented as a dynamic function that models the change in the corresponding parameter over time (**Fig. 8.3**).

The simulation structure provided for 10 conditional time units was divided into 100 intervals. The goal orientation principle (P_1) was modeled as a function with a maximum at the central time point, simulating optimal mission performance. Adaptability (P_2) had a sinusoidal character, reflecting its sensitivity to environmental changes. Crisis resistance (P_3) demonstrated monotonic growth, integration (P_4) – logistic growth, hierarchy (P_5) remained stable, and resource efficiency (P_{10}) gradually decreased over time.

The overall efficiency of the system was determined as an aggregate function of six principles with corresponding weighting factors

$$E_{total}(t)=\sum_{i=1}^{6} w_i \cdot P_i(t), \tag{8.12}$$

where w_i – the weights according to the importance of each principle.

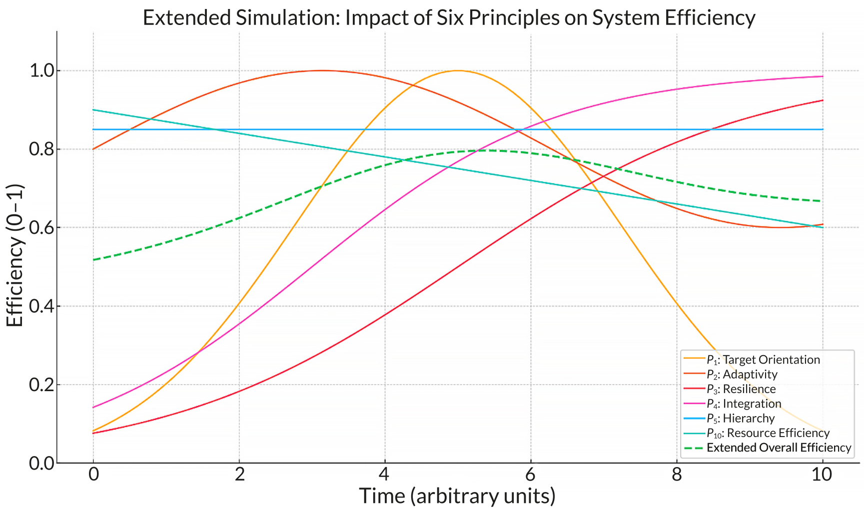

Fig. 8.3 Simulation of the impact of model principles on the efficiency of using marine robotics over time

The efficiency of the system shows a change over time, depending on the interaction of the principles. The maximum generalized efficiency is achieved when there is a balance between high crisis resistance, integration and peak goal orientation. The decrease in efficiency at the end of the simulation is due to the degradation of resource efficiency, despite the stable indicators of other principles.

The simulation showed that the effectiveness of the organizational model of the MRO is a nonlinear function of the cumulative influence of the principles. The balanced development of adaptability, crisis resistance and resource management are critical for maintaining stable operation in a dynamic environment. The results obtained can be used to develop management scenarios, optimize decisions and increase the sustainability of real-time environmental monitoring.

The simulation conducted based on mathematically formalized principles allowed for the revelation of the nature of the dynamic behavior of the organizational model of the use of marine robotics in time. The change in the indicators of adaptability, crisis resistance, resource efficiency and other characteristics was modeled in accordance with the defined functional dependencies. The aggregated efficiency of the system at each point in time was determined as the weighted value of all principles, which allowed tracing how their fluctuations affect the overall result.

To specify and expand the obtained simulation results, typical scenarios of the system functioning were formed, each of which reflects a specific combination of the values of key principles at a fixed point in time or within a certain situational model. The scenario table (**Table 8.5**) systematizes these options, allowing for the comparison of the impact of different management strategies on the overall effectiveness of the MRO functioning. Each scenario describes a unique configuration of the levels of principles, as well as the corresponding value of integrated effectiveness, which allows for assessing the advantages and disadvantages of each strategy in the context of environmental monitoring and crisis conditions.

Table 8.5 Scenarios for simulating the effectiveness of the functioning of the organizational model for the use of marine robotics

Scenario	P_1: Target orientation	P_2: Adaptability	P_3: Crisis resistance	P_4: Integration	P_5: Hierarchy	P_{10}: Resource efficiency	Overall efficiency
Baseline	0.85	0.8	0.6	0.75	0.85	0.9	0.802
Crisis growth	0.7	0.6	0.95	0.6	0.8	0.7	0.722
Resource decline	0.85	0.75	0.7	0.8	0.85	0.5	0.718
Adaptive recovery	0.9	0.95	0.85	0.9	0.8	0.75	0.848
Hierarchical optimization	0.75	0.7	0.65	0.7	0.95	0.8	0.762

The table of simulation scenarios demonstrates the variability of the functioning of the organizational model of the use of marine robotics (MRO) in different conditions, considering six key principles: goal orientation, adaptability, crisis resistance, integration, hierarchy and resource efficiency. Each scenario models a certain configuration of parameters that reflects the management or environmental situation. The base scenario is characterized by balanced values of all principles and serves as a benchmark for comparing other options. The "crisis growth" scenario models crisis conditions when the crisis resistance indicator increases, but due to a decrease in adaptability, integration and resource efficiency, the overall system efficiency does not reach high values. In the "resource decline" scenario, a significant decrease in resource efficiency is observed, which significantly affects the overall efficiency, despite the relatively high indicators of other principles. The "adaptive recovery" scenario demonstrates the highest level of overall system efficiency due to high values of adaptability, integration and goal orientation, which ensures recovery after critical situations. In the hierarchical optimization scenario, an increased level of hierarchy contributes to management stability, but an insufficient level of adaptability and crisis resistance limits the potential of the system. Comparison of the scenarios confirms that achieving high efficiency requires not only a balance between the principles, but also a priority strengthening of adaptability, integration and rational use of resources. In combination with digital technologies such as geographic information systems (GIS), virtual and augmented reality (AR/VR), machine learning (ML), the Internet of Things (IoT), blockchain, and 3D modeling, it is possible to obtain a digital model for using MRO as a tool for systematic and scientifically sound monitoring and restoration of the marine environment after disasters and post-war affected territories [27]. This ensures the comprehensive stability and flexibility of the system in a dynamic environment.

8.5 Conclusion

This section presents a holistic vision of the organizational model of the use of MRO in environmental and ecological monitoring, formed based on a structural-functional approach, considering the complex dynamics of the external environment, especially in conditions of military activity, remediation, and post-crisis recovery. Additionally, various methods aimed at mitigating these environmental impacts in the near future are considered. The constructed model encompasses three interconnected circuits – physical, informational, and managerial – which ensure its stability, adaptability, and ability for autonomous functioning. An important element is the mathematically formalized representation of ten key principles, such as goal orientation, adaptability, crisis resistance, hierarchy, integration, technological compatibility, resource efficiency, security, openness, and continuity. Such formalization allows modeling the functioning of the system in conditions of uncertainty and change, as well as creating tools for making effective management decisions based on objective criteria.

The results of the simulation modeling carried out based on the proposed model show the interdependence of the system's efficiency on the balanced implementation of the mentioned principles. A special role is played by adaptability, crisis resistance, and resource efficiency, which ensure the system's ability to respond to extreme situations. The developed system behavior scenarios make it possible to assess risks, form flexible management strategies, and contribute to increasing the sustainability of environmental and ecological monitoring and the effectiveness of measures for the restoration of aquatic ecosystems.

Thus, this research forms a scientifically substantiated basis for further improvement of management models using MRO, integrating achievements in the fields of organizational management, ecological systemology, engineering cybernetics, and simulation modeling, considering the tasks of ensuring the environmental safety of water resources.

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CHAPTER 9

Social entrepreneurship as a driver of green remediation and revitalization of affected territories: digital modeling and decision support systems

Tetiana Cherniavska
Artur Zimny
Alla Rusnak
Iryna Nadtochii
Inna Naida
Mykola Skarzhynskyi

Abstract

In the conditions of post-conflict transformation of Ukraine's territories, the issues of environmental restoration, legal transparency, and the involvement of social entrepreneurs come to the forefront in the context of sustainable development. In the present study, an integrated decision support system (DSS) has been developed and tested, in which social entrepreneurship acts as the main agent of changes. The methodological foundation of this work relies on the Triple Bottom Line (TBL), the ESG concept, which provides the operational level of measurable indicators: the *E* and *S* metrics for environmental and social results, as well as the *G* component (governance), which was implemented through a LegalTech module for the purpose of codifying the compliance requirements of smart contracts and maintaining an immutable audit trail. The empirical verification of the model was carried out on the example of the Kharkiv region, where 6 scenarios of digital integration were simulated. For visual-analytical evaluation, a Dendrogram of clusters (Dendrogram), a Parallel Coordinates Plot (PCP), and a Butterfly Chart diagram were used, which made it possible to reflect the degree of influence of digital solutions on TBL indicators, as well as to assess the degree of their influence on management efficiency. The scientific novelty of the study lies in the development of a digital model of integrative management of the processes of green remediation and revitalization of post-conflict territories relying on the tools of social entrepreneurship, which makes it possible to achieve end-to-end managerial visibility because it makes it possible to stitch together all links of the chain – data → analytics → selection → legal

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execution → cash flow → confirmed effect – into a single, verifiable orchestration. For the development of social entrepreneurship this has enormous significance, since it turns "good intentions" into contractible, financeable, and replicable projects with demonstrable impact and fair competition.

Keywords

Post-conflict transformation, green remediation, revitalization, social entrepreneurship, Decision Support System (DSS), Triple Bottom Line (TBL), ESG concept (Environmental, Social, Governance), LegalTech, GIS visualization, multicriteria analysis, simulation modeling, environmental sustainability.

9.1 Introduction

In the first quarter of the twenty-first century, the concept of restoration of territories affected as a result of military conflicts has acquired particular relevance, covering not only aspects of the physical reconstruction of objects of the housing stock and infrastructure, but also deep transformations of socio-economic, environmental, and managerial systems. Most acutely these challenges at the present moment manifest themselves in Ukraine, where, as a result of full-scale military actions, the basic life cycles of territorial communities have been disrupted, key elements of infrastructure have been destroyed, lands and water bodies are polluted, social contradictions have intensified, as well as the vulnerability of certain groups of the population. In such conditions of multifactor hybrid anthropogenic negative impact, the engagement of fundamentally new nonstandard approaches is necessary, which will be able to ensure not only the elimination of pollution from military activity, but also to form the foundations of innovative and sustainable development of the country and its regions. In this context, strategies of green remediation and revitalization acquire special significance, called upon to minimize the negative impact on the environment, restore ecosystems, stimulate economic activity, while maximally engaging social cooperation on the principles of responsibility and solidarity [1, 2].

Unfortunately, it is possible to state the fact that the projects being implemented at present in the regions testify to the predominant prevalence of fragmentary, disjointed managerial decisions, not connected into a single system and not ensuring the maximally possible synergistic effect. A significant part of such projects is focused on the rapid elimination of the consequences from military activity, while long-term social, economic, and environmental risks often remain without due attention. The management models used for the restoration of affected territories are predominantly oriented toward a vertical structure of decision-making, which are minimally aimed at the involvement of the local community and civil structures, and also insufficiently integrate modern digital technologies. This, unfortunately, leads to inefficient use of resources, duplication of functions, a low level of monitoring and control of the transparency of processes.

Social entrepreneurship, that is, entrepreneurial activity with clearly verified social and environmental goals of functioning, are increasingly considered by scholars and practitioners as an active instrument of sustainable development of local territorial communities. In many countries such enterprises have already proved their effectiveness as catalysts of regional recovery, thanks to the prompt and effective mobilization of resources, the maximally possible use of the existing potential, the attracting of attention to the projects of the local community. To a large extent thanks to their initiatives, the most acute environmental, social, economic, and political problems of a specific region "are exposed", which need the attracting of attention to them by the broad public. However, despite the presence of positive cases, their potential in the sphere of remediation and revitalization of territories affected by military conflicts remains to a significant degree unused due to the absence of systemic mechanisms of support, legal incentives, and digital tools ensuring scalability and coordination of efforts.

In the context of this it should be emphasized that the concepts of green remediation (environmentally careful elimination of pollutions of various kinds) and revitalization of territories (complex socio-economic revival of the affected territories) must occupy a central place in the strategies of post-war restoration of Ukraine. At the same time, their successful implementation cannot be implemented without large-scale use of digital technologies – from instruments of monitoring, modeling, forecasting and geoinformation systems to decision support systems (Decision Support Systems, DSS), ensuring the expediency of the use of resources, the transparency of the undertaken actions, and the observance of regulatory-legal obligations [2].

Social entrepreneurs today are recognized as a driver of positive changes in cities, regions, and in the country as a whole, taking on the solution of acute social and environmental problems by innovative methods. Unlike traditional business, the goal of social enterprises is not only profit, but also a measurable socially useful effect. Research confirms that social entrepreneurs are able to satisfy the collective needs of communities, contribute to the improvement of the quality of life of the population, and stimulate economic growth at the regional level. That is why especially relevant is their role in urban modernization, reconstruction, and revitalization. In particular, the realization of European cases demonstrates that social enterprises successfully take upon themselves the management of such projects as the restoration and revival of abandoned industrial zones, turning old factories and wastelands into cultural, educational, as well as popular modern business spaces [3].

Thus, social entrepreneurship acts as a kind of linking link between economic development, social progress, and environmental sustainability. In studies of recent years, it is noted that it is precisely social enterprises that are capable of achieving a synergistic effect at the intersection of economic growth, social justice, and protection of the environment. According to estimates of international experts, at present in the world there are about 10 million social enterprises, which generate in total on the order of 2 trillion USD of revenue and create up to 200 million jobs. All this reflects their significant contribution to global economic and sustainable development. In the context of the restoration of territories after military conflicts and other emergencies of natural and technogenic character, social entrepreneurs often act as initiators of changes "from below", relying on the knowledge of the local community, territorial specificity, allowing the maximal use of the potential resource of the local community in the implementation of socially and environmentally significant projects. As world experience shows, social entrepreneurship is capable of simultaneously solving environmental problems and creating new opportunities for the revitalization of affected territories [4].

The aim of the present research is the development of the theoretical-methodological structure of a digital model of integration management of the processes of green remediation and revitalization of post-war territories with reliance on the instruments of social entrepreneurship, modern DSS and LegalTech platforms, and its approbation.

Within the framework of the designated goal the following research tasks were defined: analysis of the transformations of post-war territories and identification of the key challenges, trends, and needs determining the specifics of green remediation and social entrepreneurship under the conditions of post-conflict recovery; identification of the possibilities and advantages of the integration of DSS, LegalTech, as well as platform models for the purpose of optimization of coordination, management, as well as scaling of the projects of remediation and revitalization of the affected territories; formation of the architecture of the digital model, combining digital modeling of the processes of remediation and revitalization, supporting decision-making, legal support of the projects implemented by the subjects of social economic activity; approbation of the model on the example of a selected case from among the most affected regions of Ukraine and, at the same time, the most active region with developed social entrepreneurship.

9.2 Theoretical and methodological basis of the research

First of all, it should be indicated what is meant in the present research by the concept of "social entrepreneurship" (SE). A comprehensive analysis of publications devoted to various aspects of such activity allows it to be defined as economic activity which is predominantly directed at the solution of social and environmental problems by means of the application of innovative business approaches. Social entrepreneurship, according to the definition of Defourny and Nyssens, represents economic activity directed at the solution of clearly defined social and environmental problems, where profit acts not as a goal, but as a means of achieving sustainable socio-environmental impact [5].

It is fundamentally important to emphasize that social entrepreneurship radically differs from traditional entrepreneurship, whose main goal is the obtaining and maximization of profit, including the satisfaction of the needs of the market, etc. Unlike traditional business, social entrepreneurship is characterized by an integrated approach, where commercial activity serves not only as a means of economic growth, but also as an instrument for solving complex social, environmental, and humanitarian challenges, thereby contributing to the sustainable development of communities and territories.

Proceeding from this, it is possible to draw the conclusion that, within the framework of the problematics relevant for post-conflict territories, the activation of activity and the scaling of social entrepreneurship (along with the development of traditional entrepreneurial activity) can facilitate a faster and environmentally careful territorial restoration of territories, at the same time creating new jobs, maximally involving local communities in the process of remediation and revitalization, introducing at the same time sustainable practices for achieving social, environmental, and economic effect. Together with this, care for future favorable post-war development ties together the use of methods of green remediation and progressive methods of revitalization of the affected territories, which cover a totality of interrelated processes, namely:

– ecological, such as the cleaning of contaminated soil, water, and air with the use of technologies minimizing the impact on the environment [6];

– infrastructural restoration of objects of infrastructure taking into account the principles of sustainability, such as the use of renewable sources of energy [7];

– social processes of involving local communities in the revival of the infrastructure of subjects of education, the creation of jobs, and the improvement of the quality of life of the population on the restored territories [8].

Social entrepreneurship, namely entrepreneurial activity with clearly verified social and environmental goals, as was mentioned earlier, in many countries plays the role of an effective instrument of the sustainable restoration of the development of the territorial socio-economic system. The studied world experience of the above-mentioned circle of interrelated issues contains many illustrative examples, presented in **Table 9.1**.

Table 9.1 World experience demonstrating the effectiveness of social entrepreneurship in the restoration of territories after conflicts, natural disasters, and environmental crises

Region/Country	Year	Description of the case	Effect of social entrepreneurship
Rwanda	1994	Program "One Cow per Poor Family" for the distribution of livestock to poor families	Reduction of poverty from 60% to 30%, ensuring sustainable sources of income, coverage of thousands of families, growth of regional GDP
USA, New Orleans	2005	Initiatives after Hurricane Katrina: restoration of schools (Doris Vuatye), return of the Vietnamese community (Father Vien), Propeller incubator for the implementation of startups	Return of 2000+ pupils and students to study, 90% return of the local population, 1000+ jobs, growth of the regional economy
Japan, Tohoku	2011	Programs of restoration after the earthquake: Tohoku Kaikon (magazine and CSA model), Otsuchi-Sashiko (embroidery), MORIUMIUS (educational center), Canyons (tourism)	16,000+ subscribers, 785,000 USD of revenue, 60 thousand+ jobs, employment for 33 thousand women, development of ecotourism, expansion of the scale to 22 regions
Philippines	2011	Programs after Typhoon Haiyan: Gawad Kalinga (housing), employment and restoration of infrastructure	3000+ houses, reduction of poverty by 10–20%, creation of new jobs, increase of the resilience of the affected territory
Nepal	2015	Field Ready (3D printing for humanitarian needs), UNDP (off-grid solar solutions)	10,000+ units of PPE, training of 100+ manufacturers, energy for 5000+ households, strengthening of the economy
Rwanda, Kenya, Ethiopia	2017	Inkomoko: support of entrepreneurs-refugees through training and microfinancing	Support of 15,000+ entrepreneurs, growth of incomes by 30%, strengthening of the regional economy
Lebanon, Beirut	2020	Live Love Recycle: separate collection and recycling of waste after the explosion in the port	Recycling of 1000+ tons of waste, creation of jobs, restoration of the urban environment
Cambodia, Ukraine	2022–2023	APOPO: demining with the use of animals; Promprylad.Renovation (Ukraine): volunteering and initiatives of restoration of territory [9]	Clearing of 100M+ m^2 of land, 200+ jobs, return of agricultural lands to operation, restoration of objects of infrastructure

By the authors of the monograph, the state and trends of the development of social entrepreneurship in Ukraine in recent times were studied in depth. Thus, in the period of military activity many social enterprises demonstrate the ability to integrate economic activity and volunteer activity with social responsibility, thereby strengthening social cohesion, increasing environmental awareness, and the economic potential of the local community. As of 2023–2025, in Ukraine there is no unified official statistics on the number of functioning social enterprises due to the vagueness of their definition and the absence of a special legal status. According to official estimates, in 2020 about 1,000 social enterprises were operating in the country [10]. Growth of their number by 82% in the period from 2014 to 2020 was conditioned by the socio-economic crisis caused by the annexation of Crimea, the war in Donbas, the appearance of new vulnerable groups and the necessity of satisfying their primary needs (it is about refugees, ATO veterans, socially unprotected groups of the population, etc.), as well as economic stagnation. In 2023–2024 social entrepreneurship became activated in response to the full-scale invasion of Russia, focusing on the support of temporarily displaced persons, military personnel and veterans, as well as on the restoration of the affected territories and the destroyed objects of infrastructure. It should be noted that the absence of a legislative base limits the popularization and scaling of social entrepreneurship, however initiatives such as for example EU4Youth promote its development through training projects and grants. State support remains weak, and financing is more often provided by grants (27%) and own revenues (54%) [11]. Social enterprises, such as Veteran Hub, demonstrate positive results in the integration of veterans, creating sustainable business models with their active participation. Online platforms, such as Diia.Business, provide free consultations and courses, supporting new entrepreneurs. However, for the purposes of the further effective development of such a type of activity, there are necessary, first of all, clear legislation, support of the government, a unified digital platform, incubators, and metrics for measuring their social impact [12].

In the opinion of the authors of the monograph, in addition to all of the above, for the systemic and balanced development of SE, ensuring a long-term effect, a stable conceptual basis is necessary. Such a basis can be the TBL concept, uniting three interrelated components:

– economic sustainability (Profit) – financial viability of projects, stimulation of development, above all, of the regional economy;

– social sustainability (People) – improvement of the well-being of the local population, as well as the creation of conditions for social inclusivity and justice;

– environmental sustainability (Planet) – minimization of the negative impact on the environment and implementation of measures for the restoration and protection of natural resources, which directly correlates with the principles of "green" remediation.

The TBL (Triple Bottom Line) concept, proposed by John Elkington in 1994, focuses attention on harmonious and balanced development through three dimensions: economic, social, and environmental sustainability. The British entrepreneur and consultant on sustainable development developed TBL for the assessment of the activity of organizations not only on the basis of financial results, but also by their impact on society and the environment. The concept received wide recognition in the 2000s, becoming a basis for assessment including also for social enterprises and sustainable business models [14].

Thus, let's consider that social entrepreneurship organically integrates all three components of TBL, at the same time ensuring their implementation in practice, especially under the conditions of post-conflict restoration of the affected territories [15, 16].

In the conviction of the authors of the present research, the ESG concept (Environmental, Social, Governance) is a direct consequence, continuation, and operationalization of the TBL concept [17]. This concept was first presented to the public in 2004 in the UN report "Who Cares Wins", where to business and investors the idea of the integration of environmental, social, and governance factors into strategy for ensuring long-term sustainability was proposed [18]. In the context of the present research, the ESG use will allow social enterprises to track in detail and manage the processes of remediation and revitalization, ensuring a high degree of transparency, efficiency, and attractiveness for external investors and stakeholders with the help of a set of concrete, measurable indicators, namely:

– environmental (environmental aspect) – indicators of the reduction of the level of pollution, restoration of ecosystems, waste management, efficiency of the use of resources, and others;

– social (social aspect) – indicators of employment, integration of vulnerable groups into the local community, social trust, involvement of the territorial community in the solution of socially significant issues, improvement of the living conditions of the population, and others;

– governance (managerial aspect) – transparency, quality of management, efficiency of the distribution of resources, compliance with legal, ethical, environmental, and other norms.

In order to integrate and effectively use ESG criteria in projects of green remediation and revitalization of territories affected by military activity in projects of social entrepreneurial activity, it is necessary to implement the corresponding digital technologies and instruments. In the context of the aggregate of questions raised in the present research, such possibilities are provided by decision support systems (Decision Support Systems, DSS) and LegalTech platforms, namely:

– collection, visualization, and analysis of data on the state of objects and the affected territory in real time;

– constant monitoring of the observance of ESG criteria and the principles of TBL;

– rapid response to changes of external conditions, as well as forecasting of risks with the possibility of operative correction of strategy;

– increase of transparency, accountability, as well as trust on the part of the local population, bodies of local self-government, donors, and investors.

In the conviction of the authors, digital modeling, DSS with platforms built into a single digital model can become those instruments that will unite social entrepreneurship, green remediation, and revitalization into a single integrated management system, based on the principles of ESG and TBL.

Summarizing all of the above, let's present the methodological framework of the research (**Fig. 9.1**).

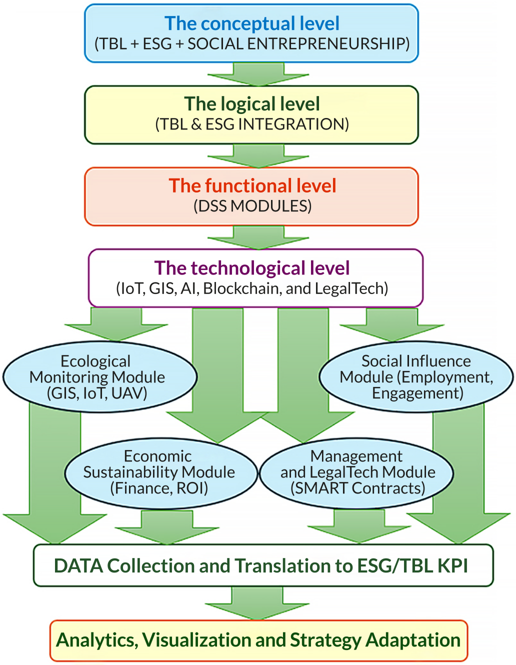

Fig. 9.1 Methodological framework of the study

The proposed architecture of the digital model integrates the TBL and ESG concepts with social entrepreneurship tools, creating a multi-level management system for green remediation and revitalization of post-conflict territories.

The conceptual level sets the methodological foundation, combining TBL (economy, society, ecology) with ESG (Environmental, Social, Governance) to provide a holistic view of sustainability.

The logical level formalizes the interrelation between ESG and TBL, allowing it to be adapted to post-conflict conditions.

The functional level is implemented through DSS modules, each responsible for monitoring ecology, assessing social impact, analyzing economic sustainability, and controlling management processes.

The technological level ensures the operation of the system using IoT, GIS, AI, Blockchain, and LegalTech.

Thus, in the present research the effective implementation of a complex of measures for green remediation and revitalization of post-conflict territories should be considered with reliance on social entrepreneurship in conjunction with the ESG (Environmental, Social, Governance) concept and TBL (Triple Bottom Line). Within the framework of the described methodology, the TBL concept sets three key dimensions – economic, social, and environmental – as balanced in the assessment of the sustainability of projects implemented by subjects of social entrepreneurial activity. In its turn, ESG expands these dimensions, including the institutional-managerial aspect (Governance), which in TBL is not directly singled out, but is critically important for the restoration of post-conflict territories. In the model under consideration, the *E*-component of TBL (ecology) can be detailed through the *E*-block of ESG (in particular, with the help of indicators of pollution of soil, water, air, and restoration of the biocenosis, etc.). The *S*-component of TBL (social) is strengthened by the *S*-block of ESG indicators, which allows one to formalize a comprehensive assessment of social inclusion, employment of vulnerable groups, and the assessment of the level of public involvement in the processes of remediation and revitalization. The economic block of TBL can be realized through ESG metrics of indicators reflecting long-term economic sustainability and the distribution of benefits among stakeholders who will participate in the processes of restoration of the affected territories. The addition of the *G*-component in ESG ensures the assessment of the level of transparency, accountability, and control of the overall effectiveness of managerial processes, including LegalTech tools and mechanisms of anti-corruption control. Thus, in the vision of the authors of the research, TBL sets a structural "triangle" of sustainability, and ESG fills its dimensions with operationalized metrics, including managerial ones. In the conviction of the authors, the integration of ESG and TBL will make it possible to build a multilevel system of comprehensive assessment, where each of the three components of the TBL concept is supported by concrete ESG indicators relevant to post-conflict restoration and the further revival of the territory. Within the framework of DSS such integration will be able to ensure a more precise, transparent, and controllable digital model, applicable both for local and regional, and for international monitoring.

9.3 Integrated digital model: architecture and characteristics of functional blocks

The aim of the digital integrated model is the support of the selection and implementation of portfolios of projects of green remediation and revitalization of post-war territories with reliance on social entrepreneurship, with measurability within the framework of the ESG concept, evaluation in the logic of TBL, transparent management by means of LegalTech, spatial binding through GIS, and provable "end-to-end managerial visibility".

Methodologically it is possible to synthesize the Mixed Methods approach, digital convergence, and triangulation. The architecture of the digital model will also include a Data Mesh of socio-geospatial and contractual data, robust normalization and accounting for the polarity of indicators, AHP/ANP weighting with calibration, explainable predictive analytics (GBDT/LSTM/GAM), scenario analysis with MCDA, multi-period optimization of the portfolio of projects (with precedence UXO → remediation and CVaR risk), and GIS assessment of spatial effects.

The general characteristic of the structural elements of the unified digital model proposed by the authors and their formalization is presented in **Table 9.2**.

The data of the table demonstrate how each module of the digital model (data → indexes → weighting model → MCDA → optimization → LegalTech → GIS → monitoring) is supported by formulas and tied to goals/threshold values. The aim of the authors of the monograph was to develop such a digital model that the key parameters and the obtained results of the projects could be instruments of management by means of the visualization tools used: Butterfly Chart (for the visualization of progress/gaps), Parallel Coordinates Plot (PCP) (for the visualization of profiles by the scenario and utility-U), Dendrogram (for the visualization of clusters). In the conviction of the authors, this will make it possible to ensure end-to-end managerial visibility and reproducibility of effective solutions.

Table 9.2 Architecture and formalization of the digital model by modules (end-to-end contour)

Layer/module	Purpose	Key inputs/parameters	Mathematical formalization
Data Mesh (S/E/I/C/G)	Integration of data	*S*: register of social enterprises (id, NAICS/NACE, region, FTE, SROI, capex/opex); *E*: soil, water, air, UXO, biodiversity, coords; *I*: donor, amount, instrument; *C*: contracts (id, value, terms, awardee, social_enterprise, milestones, payments); *G*: land use, damage, access, grid	–
Cleaning from pollution and normalization of the territory	Comparability of scales and robustness	Pollution, standards, units of measurement, standards	Robust z-score: $z = (X - \text{median}(X))/IQR(X)$; scale to [0,1]; inversion for "↓ better": $X+ = 1 - \text{scaled}(X)$
Indexation ESG → TBL	Indexes of branches and KPI	Indicators $E1…E5$, $S1…S4$, $P1…P5$, $G1…G5$	$E^{\backslash *} = \sum j w_{E,j} E_j^{norm}$, similarly for S^*, P^*, G^*; $\sum jw\_((.), j) = 1$
Weighting model	Prioritization of branches	Top-level weights ($\alpha, \beta, \gamma, \Delta$)	$CR \leq 0.10$; monotonic constraints; log of versions of weights. For the pilot project: $\alpha = 0.35, \beta = 0.25, \gamma = 0.25, \Delta = 0.15$
Definition of utility (MCDA)	Compensatory evaluation of scenarios	E^*, S^*, P^*, G^*, weights	$U(s) = \alpha E^*(s) + \beta S^*(s) + + \gamma P^*(s) + \Delta G^*(s)$; ranking of scenarios $S1...S6$; leaders: $S6$, $S4/S5$
LegalTech (Governance)	Transparency and control over the fulfillment of contracts	Events of tender/contract, templates of smart payments, risk assessment, rules	$LT_{(C)} = \lambda_1 \mathbf{1}_{e-tender} + \lambda_2 \mathbf{1}_{e-contract} + + \lambda_3 smart - \lambda_4 P(violation) \cdot Impact$; subject to the hard constraint $x_{rem} \leq \sum_i x_{\text{UXO},\, i}$
Forecast + XAI	Forecasts of KPI and their explainability	Time series S/E/I/C/G; scenarios	GBDT (Cat/XGB) + LSTM + GAM; conformal intervals; SHAP/ICE
Optimization of the portfolio	Selection of x^* by years/clusters	Budgets Bt deadlines $T_{\max}$, thresholds, fairness	x^*, roadmap, plan of KPI payments
GIS integration	Spatial analysis	Geometries of projects, logistics, determination of problem zones	Cost-distance, overlay/clip, zonal statistics
Monitoring/ visualizations	Control of progress	Base 2026H1, goals 2030, facts/oracles	Butterfly Chart, PCP, Dendrogram, dashboards of G-metrics. Progress toward goals by KPI; profiles E^*, S^*, P^*, G^*, U clusters $C1–C3$
Validation/ assessment of readiness of the model	Check of quality and compliance with current tasks	DQ, MAPE, ECE, fairness, lead-time, PDK	Threshold criteria: DQ, MAPE, ECE, P(PDK); P(\mathrm{PDK}) and others

9.4 Approbation of the integrated digital model on the example of Kharkiv region (Ukraine)

Kharkiv region remains one of the most active ecosystems of social entrepreneurship in Ukraine: despite the proximity to the zone of hostilities, in the region there function on the order of 100–150 SE (estimate for 2024), predominantly supported by international donors (such as USAID, EU4Business, the "Renaissance" Foundation, etc.) and local infrastructure (including the Union of Entrepreneurs of Kharkiv region, the initiatives of the regional military administration, etc.). Undoubtedly, the military situation restrains the scaling of the development of SE, however, along with this, confirms also the popularity of the given business model in the region [19].

Below in **Table 9.3** the passport of the ecosystem of social entrepreneurship of Kharkiv region is presented.

Table 9.3 Passport of the ecosystem of social entrepreneurship (identification card, 2024)

Parameter	Description	Comment/sources
Region	Kharkiv region, Ukraine	Approbation of the pilot for DSS/LegalTech/GIS
Period of the baseline assessment	2024 (calendar year)	Used as the baseline cut before the launch from H2-2026
Number of social enterprises	≈ 100–150	Indirect estimates from open sources
Key directions of social entrepreneurship	Inclusion, ecology, education/culture, social assistance	Profiles are used for the setting of *S*-metrics
Examples of initiatives	"Wardrobe of Good" (2017–2024, assistance to pregnant women and unprotected groups of the population); cooperatives for waste processing	Illustrative cases of the ecosystem
International support	USAID (micro-grants ~ 20 thousand USD for SMEs with a social mission); EU4Business (up to 25 thousand EUR); Renaissance Foundation	Channels of financing and SROI data
Created infrastructure	Union of Entrepreneurs of Kharkiv region; departments of the regional administration (social protection)	Consulting, training, legal support
Current constraints of the development of SE	Proximity to the front, martial law → risks, logistics, deficit of resources	Important inputs for CVaR and planning
Relevance and completeness of the data	2024–2025; partial coverage	For the purpose of filling gaps – requests to the regional administration/donors
Main open sources of information	Nakipelo.ua; USAID; EU4Business/USF; Renaissance Foundation; YouControl	For the purpose of verification and updating of the passport

In the opinion of the authors of the monograph, the data of the SE passport of the region selected for approbation can be organically embedded into the previously formed digital model, namely:

– *S*-layer (social entrepreneurship): entry of data into the register of SE and their profiles → employment of target groups (*S*1), participation in the project of the local community (*S*2), social assistance and support/training/rehabilitation of groups of the population in need of this (*S*3), localization of procurements for the implementation of projects (*P*3 through counterparties of social entrepreneurship);

– *C*-layer (contracts): determination of the main channels of financing and implementation of procurements → e-tender/e-contract, smart-coverage (*G*2/*G*3), LT risk scoring (*G*4), lead-time (*G*5);

– *E*-layer (ecology): projects of social entrepreneurship in the context of elimination of pollution from military activity/reconstruction/green remediation of territories affected by military activity → integration into the metrics *E*1–*E*5 and the coverage map $Z(x, y)$;

– *I*-layer (investments): financial and humanitarian assistance/grants/microfinancing → trajectory of CAPEX/OPEX and pay-for-impact scenarios.

In the opinion of the authors of the monograph it is necessary to clearly designate the boundaries and the regime of approbation of the digital model:

1. Start of works: not earlier than H2-2026; planned horizon until 2030.

2. The necessity of distinguishing key scenarios, namely, 6 scenarios of digital integration (*S*1–*S*6) with different share of SE and LegalTech coverage:

– *S*1 – Bio/Phyto: focus on bio- and phytoremediation [20]; basic LegalTech (e-tender), a moderate share of participation of subjects of social entrepreneurship;

– *S*2 – Remed + Green Housing: remediation + construction/modernization of "green" housing for temporarily displaced persons and for returned residents of Kharkiv region; basic LegalTech coverage;

– *S*3 – Remed + Inclusion + LegalTech: remediation with a priority of social inclusion (employment of vulnerable groups of the population, access to receiving services of education [21], medical aid and medical servicing of all groups of the population [22]) and reinforced LegalTech (e-contract, KPI payments);

– *S*4 – Multi (eco + energy + agro + LT + DSS): intersectoral package (ecology, the use of alternative sources of energy [7], revival of the agro-industrial potential [23] with integrated DSS and LegalTech; balanced portfolio;

– *S*5 – Circular/Energy & Water Reuse: projects of circular economy (connected with recycling, industrial symbiosis, etc.), reuse of water/energy; smart contracts in the context of transparent implementation of projects of the circular economy [24];

– *S*6 – Integrated + Governance Max: maximal integration with full LegalTech orchestration (including mechanisms and instruments of e-tender/e-contract/smart [25]), high participation of social enterprises, strict UXO → Remediation – the hard constraint.

3. Reasoned choice of the visual-analytical package in the composition: dendrograms (clustering of territories), PCP (E^*, S^*, P^*, G^* and utility U), Butterfly Chart (for the visualization of the progress of achieving goals, as well as the visualization of gaps).

4. GIS analysis: geography of placement of social enterprises and the territorial analysis of consumers in remediation, analysis of transport accessibility, analysis of territories of agricultural designation, objects of water and energy supply, and UXO zones (territories with unexploded ordnance) → prioritization of locations of remediation and the contours of "UXO → Remediation" [26, 27].

Approbation of the digital model was conducted as an ex-ante pilot for Kharkiv region (horizon H2-2026 → 2030), with the starting base 2026 H2 and target normalization of KPI by 2030. The S/E/I/C/G data were collected in a Data Mesh with quality verification (DQ-SLA), robust normalization (robust z-score, taking polarity into account), and then subsequent aggregation into branch indices E^*, S^*, P^*, G^*. The top-level weights α, β, γ, Δ were determined by us through AHP/ANP and were calibrated by learning-to-rank. Forecasts of the target indicators Y were built by a stack of GBDT + LSTM + GAM with conformal calibration (95% PI) and XAI (SHAP/ICE), and the causal part was evaluated by a DiD design with PSM selection of control locations (pre/post), which made it possible to separate the effect of the portfolio of projects from background trends. The scenarios (*S*1–*S*6) were compared in MCDA; further a multi-period MILP/ε-constraint optimization of the portfolio x^* was performed with hard precedence UXO → Remediation, budget/calendar constraints, fairness quotas, and CVaR constraints by deadlines/cost. The level of probability and uncertainty was evaluated with the help of the Monte Carlo method ($N = 5{,}000$). Spatial effects were analyzed in GIS by the coverage function $Z(x, y) = 1 - \prod(1 - \phi p\ up\ xp)$ taking into account cost-distance and barriers. The prioritization of territories for clearance from military contamination and subsequent remediation was refined by the dendrogram with the help of cluster-dependent weights. For governance, LegalTech orchestration was applied: rules of Compliance-as-Code, e-tender/e-contract, smart payments pay-for-impact and LT risk-event scoring; KPI were confirmed by "oracles" (registries/GIS/IoT), and execution events were recorded in WORM logs. The visual-analytical package included PCP (profiles E^*, S^*, P^*, G^*, U, Butterfly Chart (progress/gap to the goals of 2030), and Dendrogram (clustering of territories).

As a result, the approbation of the digital model carried out showed that with the horizon H2-2026 → 2030 the portfolio x^* ensures substantial progress on ecology and manageability of projects: remediation of soil and water resources approaches the established standards ($E1\ \Delta \approx -29$ p.p.; $E2\ \Delta \approx -16$ p.p., DiD are significant), UXO-cleared grows by ≈ +37 p.p. for the portfolio, and risk ($G4$) decreases to the indicator 0.17 with the simultaneous reduction of lead-time from 48 to 26 days. The social results are confirmed: increase of the level of employment + ≈ 680 FTE (with a focus on vulnerable groups of the population, *author's note*), participation of the local community in socially and ecologically significant projects +0.21; social assistance/training/rehabilitation ≈ 1200 participants. The economic block is stable: median IRR ≈ 11.4%, SROI ≈ 2.3, at the same time local procurements grew from 0.34 to 0.55 (DiD ≈ +0.19), but remain among the key zones of fine-tuning along with the bio-index ($E5$). Air cleaning ($E3$) demonstrates a positive trend ($\Delta \approx -8$ p.p.), however statistical significance is on the verge ($p \approx 0.08$) due to weather volatility – extended observation and additional analysis of weather regressors are required. Integrally $U(x^*) = 0.682$ at $(\alpha, \beta, \gamma, \Delta) = (0.35, 0.25, 0.25, 0.15)$; robustness is confirmed (IQR [0.666; 0.691], rank stability amounts to ~92%), the indicators of the level of risks are within the norm ($CVaR_{95}$ deadlines 12.4%, CAPEX 9.2%). The spatial effect increased: average $Z(x, y)$ from 0.18 to 0.47, zone $Z \geq 0.6 \sim 1{,}850$ km^2, logistics improved (cost-distance −13%). LegalTech orchestration ensures e-tender ≈ 93%, smart-coverage ≈ 68%, 17 out of 19 anomalies were identified and successfully settled; violations of SLA > 30 days – 0.

The data of the **Table 9.4** presented below confirm the fact that the pilot for Kharkiv region passed key checks of data quality, forecast accuracy, and managerial effects. Completeness of critical fields (DQ) amounted to 96.8% with a target ≥ 95% – the source data are sufficient for reliable computations. Forecast accuracy (MAPE) for targets Y fit into the threshold ≤ 15% (range 11.9–16.2%); the only exception – SROI with 16.2% (on the edge of admissible with reservations, *author's note*). Calibration of the risk model (ECE = 0.028) corresponds to the requirement ≤ 0.03, that is, the probabilistic estimates of risk are not systematically overestimated/underestimated, which is acceptable. Reduction of managerial risk ($G4$) reached ≈ −47% with a target −30%, and the share of achievements of MPC in the cores – ≈ 82% (target ≥ 75%), which confirms ecological effectiveness. The principle of fairness (fairness) is observed (at least one project in each cluster annually), and lead-time decreased by approximately −46% with a target −25%, which reflects the effect of LegalTech orchestration. Taken together, the criteria indicate the conformity of the approbated digital model to the acceptance conditions and its readiness for scaling; at the same time, it is expedient to strengthen the SROI block (expansion of the sample, quantile loss, refinement of external effects is recommended).

Table 9.4 Validation and criteria of the overall assessment of the approbation of the digital model

Criterion	Target	Fact	Status
DQ completeness of critical fields	≥ 95%	96.8%	✓
MAPE for *Y*	≤ 15%	11.9–16.2%*	(SROI 16.2%)
ECE (risk calibration)	≤ 0.03	0.028	✓
Reduction of G4	−30%	≈ −47%	✓
MPC in cores (to Tmax)	≥ 75%	≈ 82%	✓
Fairness (≥ 1 project/cluster/year)	Yes	Yes	✓
Lead-time (median)	−25%	≈ −46%	✓

*Note: * for SROI MAPE = 16.2% – acceptable with a note: high dispersion of external effects. In the plan – to expand the training sample and apply quantile loss*

The visualization of the approbation results of the digital model using the example of Kharkiv region is presented in the figures below (**Fig. 9.2–9.4**).

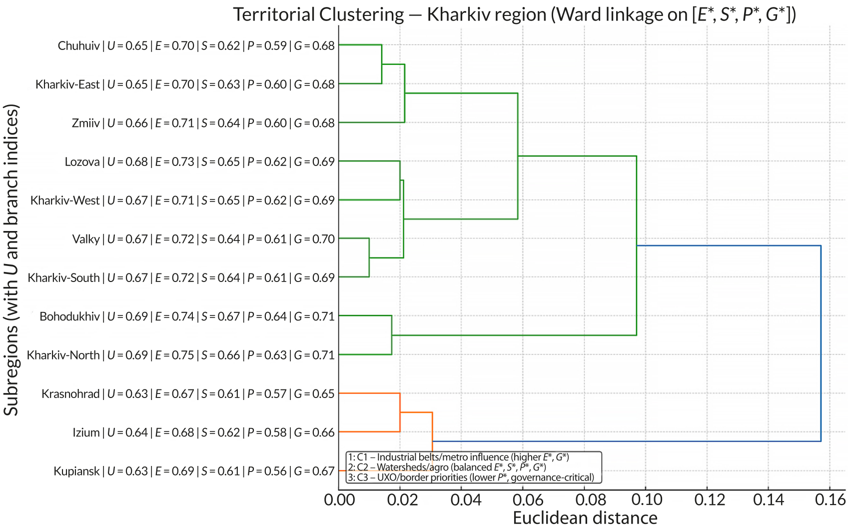

Fig. 9.2 Dendrogram: subregions of Kharkiv region (by E^*, S^*, P^*, G^*)

Let's note that the presented dendrogram performs hierarchical clustering of the subregions of Kharkiv region by the vector of normalized indices [E^*, S^*, P^*, G^*] (Ward linkage; Euclidean distance). On each segment of the dendrogram the integral utility U and the branch values are indicated: in the "metropolitan" zones (Kharkiv-North/South/East/West, Bohodukhiv) $U \approx 0.67–0.69$ with comparatively high E^* and G^* – this is cluster *C*1. *C*2 (Lozova, Valky, Zmiiv) – balanced agro/catchment territories with $U \approx 0.66–0.68$. *C*3 (Izium, Kupiansk, Krasnohrad, Chuhuiv) – UXO/border profile with lower P^* ($\approx 0.57–0.59$) and $U \approx 0.63–0.65$, which singles them out as a zone of increased managerial attention. The greatest "height of merging" between *C*1 and *C*3 indicates the greatest structural distinctness and the necessity of a differentiated policy.

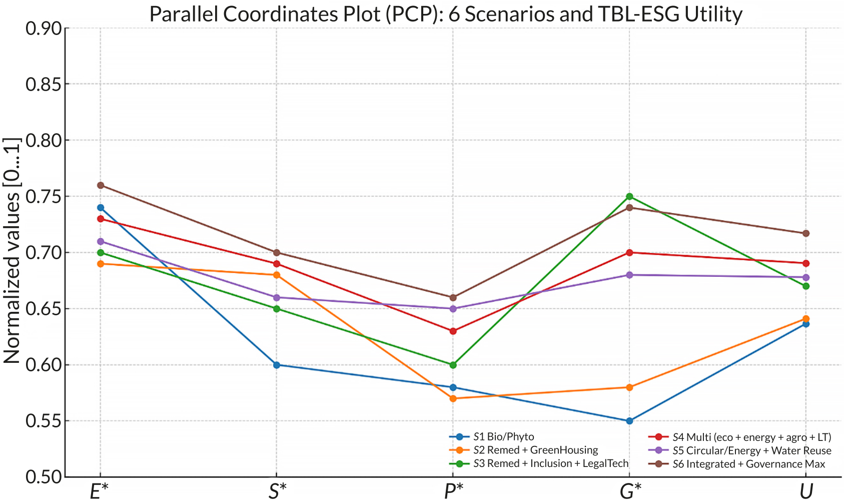

Fig. 9.3 Parallel coordinates plot (PCP): 6 scenarios and TBL-ESG utility

The Parallel Coordinates Plot presented above visualizes the profiles of six scenarios (*S*1–*S*6) by the normalized branch indices E^*, S^*, P^*, G^* (scale 0...1) and the final utility U. As can be seen from the data of the chart, the leader is scenario *S*6 Integrated + Governance Max: $E^* = 0.76$; $S^* = 0.70$; $P^* = 0.66$; $G^* = 0.74$, which gives the highest utility indicator $U \approx 0.72$. Scenario *S*3 Remed + Inclusion + LegalTech stands out with a maximal $G^* \approx 0.75$ with a moderate $P^* \approx 0.60$, providing at the same time a quite high, but not the best, utility indicator U. Scenario *S*4 Multi is rather balanced ($E^* \approx 0.73$; $S^* \approx 0.69$; $P^* \approx 0.63$; $G^* \approx 0.70$; $U \approx 0.69$). Scenario *S*5 Circular/

Energy is quite close by the integral utility result ($U \approx 0.68$). Scenario $S1$ Bio/Phyto is strong in environmental effectiveness ($E^* \approx 0.74$), but weaker in S^*, P^*, and G^* ($\approx 0.60/0.58/0.55$) – $U \approx 0.64$; scenario $S2$ Remed + GreenHousing is constrained by low $P^* \approx 0.57$ and $G^* \approx 0.58$ with a good level of indicators $S^* \approx 0.68$ – $U \approx 0.64$. The intersections of the lines on the axes show trade-offs: strengthening Governance (G^*) and the overall balance of metrics raise the U indicator even at an average level of P^*.

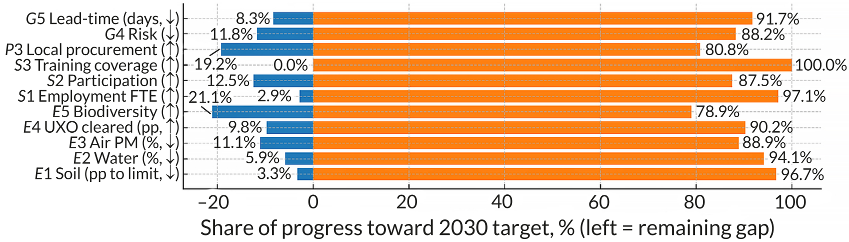

Fig. 9.4 Butterfly chart: progress to the goals (2026 H2 → 2030, Kharkiv region)

The Butterfly Chart presented above reflects for each KPI the share of progress toward the goals of 2030 (right/orange wing) and the remaining gap (left/blue wing) from the baseline level 2026 H2 for Kharkiv region. The strongest positions are observed for the scenarios: $S3$ Training – 100%, $S1$ Employment – 97.1%, as well as ecology $E1$ Soil – 96.7% and $E2$ Water resources – 94.1%. As is seen, the managerial indicator $G5$ Lead-time is close to the goal – 91.7%. The middle echelon of indicators covers the following blocks: $E4$ UXO cleared – 90.2%, $E3$ Air (PM) – 88.9%, $G4$ Risk – 88.2%, $S2$ Participation of SE in projects of remediation and revitalization – 87.5%. The main lags are observed in: $E5$ Bioindex (78.9%, the gap amounts to 21.1%) and $P3$ Local procurements (80.8%, the gap amounts to 19.2%), which points to priority zones of fine-tuning of the policy of resource provision of the region.

9.5 Conclusion

The research result is the confirmation of the thesis that social entrepreneurship acts as a driver of green remediation and revitalization: through the involvement of the local community in the process of restoration of the affected territories, employment of vulnerable population groups, assistance and support to the affected and temporarily displaced persons, localization of supply chains and transparency of the implementation of projects. Moreover, it is capable of turning the goals of sustainable development into contractable and scalable projects. The theoretical-methodological basis of the research rests on the bundle TBL → ESG (for the purposes of evaluation and operationalization), DSS (for the purposes of selection and optimization of managerial decisions) and LegalTech (for the purposes of transparent legal execution), united in a single architecture with Data Mesh, GIS, multi-criteria analysis (MCDA) and robust portfolio optimization (including CVaR). The scientific novelty consists in the orchestration of TBL–ESG, DSS, LegalTech and GIS in one end-to-end contour "data → analytics → decision → contract → KPI payments → confirmed effect", which ensures manageability and verifiability of impact. Approbation on the example of Kharkiv region (horizon of forecast modeling: H2-2026 → 2030) showed the attainability of the target trajectories, namely: high levels of progress in increasing the level of employment and training, substantial convergence of the indicators of cleaning of soil and water resources in accordance with the standards, growth of the share of UXO-cleared and noticeable improvement of the indicators of manageability (in particular, reduction of the level of risk, as well as acceleration of the procedures of remediation and revitalization). The visual-analytical package (Dendrogram, PCP, Butterfly Chart) demonstrated transparent profiles of scenarios and differences of territories subject to clearance from military contamination and subsequent remediation, which made it possible to adapt the weights and thresholds by clusters and to reduce the "bottlenecks" of implementation. The practical value of the model is in ensuring end-to-end managerial visibility for the authorities, the local community, investors and donors, in the reduction of transaction costs through e-tender/e-contract and pay-for-impact smart payments, as well as in the creation of predictable conditions for the financing of projects of the development of social entrepreneurship.

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