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DIGITAL RECONSTRUCTOR: INTEGRATION OF DIGITAL TWINS FOR THE RECONSTRUCTION AND REMEDIATION OF WAR-AFFECTED TERRITORIES IN UKRAINE

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Abstract

This article provides a comprehensive analysis of the potential and opportunities of Digital Twin technology for the reconstruction and remediation of socio-economic and ecological systems in Ukraine. Given the scale of destruction caused by military activities, limited resources, and tight recovery timelines, traditional remediation methods often prove too slow and resource-intensive. To address this, the authors propose a project aimed at implementing Digital Twin systems for the integrated restoration of infrastructure in these systems. Virtual models of war-damaged infrastructure (roads, bridges, buildings) and ecosystems (forests, water systems) will be created using geospatial data, sensors, and real-time monitoring technologies, enabling timely responses, effective decision-making, and efficient resource management. The study examines successful applications of Digital Twins and discusses their challenges and prospects within sustainable development. The results confirm that the adoption of Digital Twin technology can significantly enhance post-war recovery efforts. The authors' future research will focus on successful digital transformation experiences and the development of frameworks to optimize the integration of Digital Twins into Ukraine's post-war remediation management model.

Keywords: Digital Twins, Digital Technologies, Remediation, Infrastructure, Ecosystem, Socio-Economic System, Digital Transformation.

INTRODUCTION

The optimally rapid and effective recovery of war-affected territories is one of the most pressing issues currently on Ukraine's agenda, as active military operations continue to this day. The destruction of industrial, social, and transport-logistics infrastructure, along with the damage inflicted on the population, presents significant challenges for the country's recovery. In this context, progressive innovative solutions are critically important, as they can contribute to the effective and sustainable restoration of the national socio-economic system as a whole. One such solution is the implementation of Digital Twin (DT) technology, which has the potential to drastically transform the management of logistics processes, infrastructure restoration, and significantly aid in environmental remediation. The relevance of this study lies in the need to explore how the use of Digital Twins can optimize Ukraine's efforts in remediating the socio-economic and ecological system, ensuring faster, more sustainable, resource-efficient, and effective reconstruction processes of damaged and/or destroyed objects.

The significance of this research is that Digital Twin technologies have already proven to be an effective tool for restoring damaged systems and infrastructure in other countries, particularly in post-disaster recovery situations. Many countries have successfully integrated Digital Twins into their recovery and reconstruction strategies, especially after natural disasters. For example, Japan used Digital Twins following the 2011 tsunami and earthquake as part of the infrastructure recovery program. Similarly, the Netherlands employed Digital Twins for flood management to increase infrastructure resilience in flood-prone areas. Singapore applied this technology for managing the recovery of urban infrastructure after severe flooding, and the United States used Digital Twins to rebuild infrastructure after Hurricane Katrina, specifically for the reconstruction of levees. Germany also applied Digital Twin technology for post-flood recovery in 2013, which helped optimize the implementation of restoration works and efficiently allocate resources. These examples demonstrate the effectiveness of Digital Twin technology in managing recovery operations and minimizing the consequences of future crises (Van Looy, 2024; Lagap, Ghaffarian, 2024; Abayadeera, Ganegoda,2024; Pasupuleti, 2024).

The objective of this study is to provide a comprehensive analysis of the potential of Digital Twin technology, which can be used in Ukraine for reconstruction and remediation efforts of the socio-economic and ecological systems.

The author's hypothesis is that the implementation of Digital Twins into the post-war reconstruction and remediation process in Ukraine will not only accelerate recovery but also reduce costs, improve resource allocation, and create more resilient infrastructure capable of withstanding future challenges. By studying the successful use of this technology in other countries and analyzing its potential application in Ukraine, this research aims to provide valuable recommendations on the role of Digital Twins in optimizing post-conflict recovery.

MATERIALS AND METHODS

In the framework of this research, for the purpose of the project implementing Digital Twin technology into Ukraine's remediation strategy, a set of scientific methods is used, which form the "core" of the methodological model, as well as "peripheral" methods that help find solutions to specific tasks.

Thus, the "core" of the methodological model consists of the following scientific methods:

Digital Twins – a key tool that allows the creation of virtual models of objects, which enables effective monitoring and optimization of restoration processes, damage assessment, and resource allocation for their reconstruction.

Simulation Modelling – used to create various scenarios for reconstruction and remediation, which will allow for a comprehensive analysis of potential outcomes of actions taken under different conditions during remediation efforts, aiming to minimize risks and overall costs.

System Approach – applied to analyze and synthesize various elements of the socio-economic and ecological systems and their interactions, allowing the entire recovery process to be studied as a unified, interconnected system.

Comprehensive Approach – focused on analyzing all aspects of restoration (economic, social, ecological) and their integration within a single project, contributing to a more holistic and effective restoration process.

Integration Approach – implies the integration of various technologies and solutions, such as Digital Twins, IoT, AR/VR, and other progressive technologies, to create a unified platform that will effectively aggregate real-time data in the reconstruction and restoration processes.

Optimization Approach – used to find the most effective options for reconstruction and remediation from all available alternatives, considering limited resources and time constraints, which will ensure maximum efficiency and resilience with minimal costs.

Synergistic Approach – allows for the investigation of the combined complex influence of various factors and elements, creating synergies between different technologies, approaches, and methods, which will contribute to improving results and accelerating the restoration of Ukraine's war-affected territories after the completion of military operations (Kumar, 2024; Shafik, 2024; Bibri et all., 2024; Yu, Mahamadu, Chen, 2024).

The complementary scientific methods include:

Project Method, which is used for structuring the entire restoration process as the "Digital Reconstructor" project, with a clear definition of goals, tasks, timelines, and resources, helping to organize the work and effectively manage the restoration process.

Situational Approach, which is applied for analyzing current situations on the ground, allowing for rapid response to changes in the restoration process and adapting actions based on new circumstances.

AR/VR – Augmented and Virtual Reality technologies are used for visualizing restoration processes, as well as for modelling and assessing the consequences of various managerial decisions.

IoT (Internet of Things) – used for collecting real-time data through various sensors and devices, enabling continuous monitoring of the condition of territories and objects, and providing the ability to respond quickly to changes.

ML (Machine Learning) – applied for analyzing large volumes of data and predicting future changes in the restoration process, helping to improve decision accuracy and resource management.

GIS (Geographic Information Systems) – used for mapping and analyzing territories, assessing the scale of damage, as well as for optimizing logistics processes and planning restoration.

Scenario Approach – allows for modelling different development scenarios in the remediation project, facilitating better forecasting and preparation for possible risks.

Strategic Approach – focused on long-term planning for the restoration and development of war-affected territories, ensuring sustainable and balanced growth in the future.

Resource Approach – used for effective distribution of limited resources (material, human, financial), allowing for minimized costs and ensuring optimal use during the implementation of the remediation strategy (Gupta, Iyer, Kumar, 2024; Hananto et all., 2024; Riaz, McAfee, Gharbia, 2023; Sanfilippo et all., 2022;).

RESULTS

It has already been 1000 days since the second largest war in European history in terms of scale and destruction (after World War II – author's note) began in Ukraine. Experts predict that the clean up and remediation of the environment and socio-economic infrastructure after the Russian invasion may take decades. History shows that this is an optimistic version. According to the Ukrainian Ministry of Environmental Protection, the total financial losses amount to 62.9 billion USD (as of mid-September 2024) (Fig. 1) (Ovchinnikov, 2024; Uhlig, 2024).

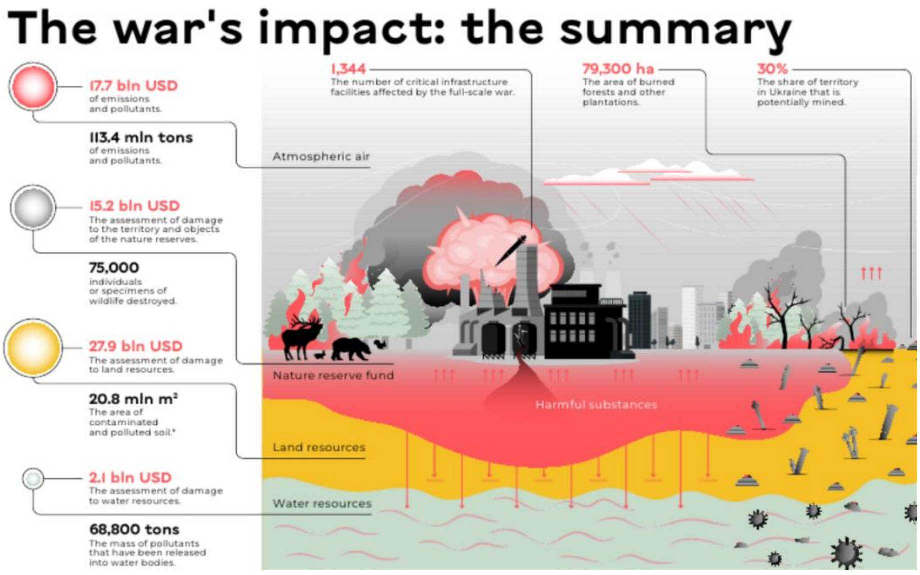

Figure 1. The overall scale of losses and damage from military activities in Ukraine*

* *Source: https://uwecworkgroup.info/environmental-consequences-of-the-war-in-ukraine-july-2024-review/*

Monthly, Ecodosor – the national platform of Ukraine that tracks war-related losses – provides information about the damage caused to homes, industrial enterprises, infrastructure, fuel storage facilities, raw materials, munitions, or industrial waste (Fig. 2).

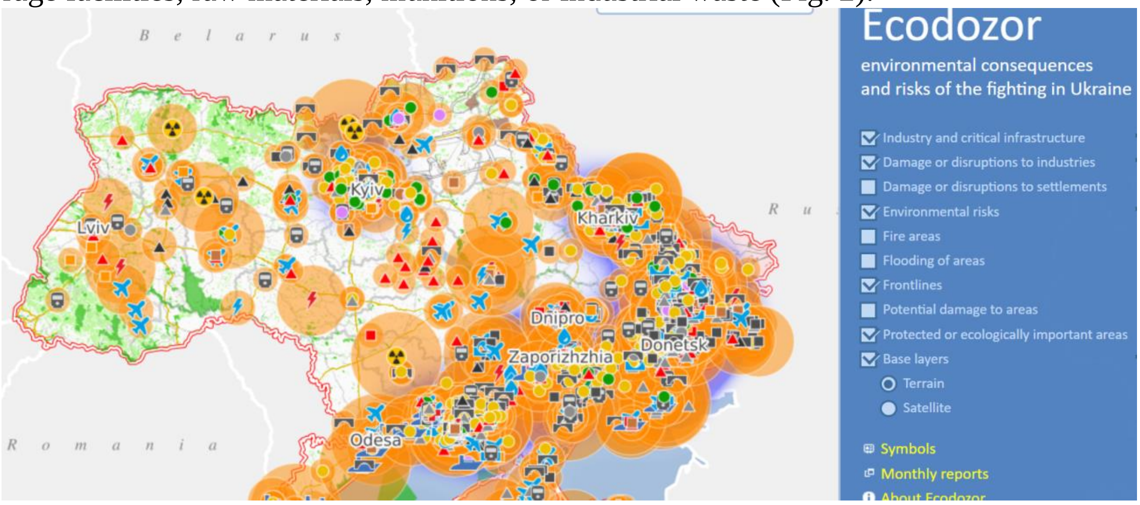

Figure 2. Cartographic analysis of the environmental consequences and risks of military actions in Ukraine

(Available at: https://ecodozor.org/)

According to the published data from the Ecodosor platform, from February 2022 to October 2024, the total damage includes 3204 incidents at 1661 facilities across Ukraine, including 76 incidents in 66 settlements in October 2024 (see Table 1) (Uhlig, 2024).

To ensure effective reconstruction and remediation of war-affected territories in Ukraine, we propose a project aimed at implementing a Digital Twin system for the comprehensive restoration of infrastructure objects within socio-economic and ecological systems.

Table 1 The number of cases of disruption and accidents at critical infrastructure facilities in Ukraine due to military activities*

Sector[1]	February 2022 — October 2024		October 2024	
	Number of facilities	Number of incidents	Number of facilities	Number of incidents
Metallurgy and metal processing	35	131	1	1
Chemical and coke-chemical industry	71	260	3	3
Mining	83	370	7	10
Machine building	122	218	6	6
Glass work	3	9	-	-
Construction	51	80	1	1
Thermal power	27	168	2	2
Hydropower	6	34	-	-
Solar and wind power	9	11	-	-
Nuclear power	9	216	1	2
Food industry	120	160	2	2
Agriculture	230	261	10	10
Power grid facilities	105	120	2	2
Fuel supply	106	125	4	4
Water and waste water	50	67	2	2
Airports and airfields	53	147	1	1
Ports	23	94	5	6
Railway infrastructure	89	137	4	5
Bridges	149	241	6	6
Light industry	12	13	-	-
Wood processing and pulp-and-paper industry	31	37	-	-
Medical industry	4	4	-	-
Dams and dykes	25	31	-	-
Other	248	269	9	12
Total:	**1661**	**3204**	**66**	**76**

[1] Heavy industry, Power generation, Food and agriculture, Resource supply, Transport, Other

* Source:https://ecodozor.org/report/report.php?month=2024-10&lang=en

In order to ensure the effective reconstruction and remediation of war-affected territories in Ukraine, we propose a project aimed at implementing a Digital Twin system for the comprehensive restoration of infrastructure objects within the socio-economic and ecological systems.

As previously described, Digital Twin technology has already proven to be highly effective in global practice in cases of post-disaster recovery. However, in the context of the situation Ukraine faces, where the destruction and damage to infrastructure were caused not by natural disasters but by military actions, Digital Twins can play an even more crucial role. The authors believe that this simulation modeling tool can significantly expand its application in the reconstruction and remediation of affected territories by providing a more accurate and efficient assessment of damages, designing, planning remediation efforts, and resource allocation (Horst et all., 2018; Horst et all., 2020).

It should be noted that Digital Twins allow for the creation of virtual replicas of destroyed infrastructure objects such as roads, bridges, buildings, energy systems, and water supply systems. First and foremost, this enables a detailed 3D analysis of damages and identifies the most critical elements that require immediate restoration (Riaz, McAfee, Gharbia, 2023; Hananto, et all., 2024; Sanfilippo et all., 2022).

Furthermore, Digital Twins can effectively integrate with other modern technologies such as the Internet of Things (IoT), Machine Learning (ML), Geographic Information Systems (GIS), and Augmented Reality/Virtual Reality (AR/VR), allowing for real-time data collection, forecasting potential threats, and responding to changes in the situation. For example, by using sensors and IoT devices installed on infrastructure objects, it is possible to monitor their condition in real time, which helps to quickly identify damages and plan repair work (Dianyou, He, 2022; Vieira et all., 2024;).

In addition to the above, Digital Twins can be used for ecological remediation, including the restoration of ecosystems contaminated by military actions. With the use of Digital Twins, it is possible to accurately model the spread of pollutants such as chemicals, munitions, and oil, and analyze their impact on the ecosystem. This enables more efficient planning of pollution remediation and ecosystem restoration efforts, minimizing overall costs and health risks for the population (Ranatunga et all., 2024; Schigel, 2024).

All of the above supports the hypothesis that Digital Twin technology is a powerful tool for a comprehensive approach to the reconstruction and remediation of war-affected territories. The inclusion of Digital Twins in the post-war remediation strategy of Ukraine will accelerate recovery efforts, enhance their effectiveness, and ensure more sustainable development for the country in the future.

In general, the scope of Digital Twin applications can be outlined as follows:

1. Creation of 3D models for remediation objects. A Digital Twin serves as an accurate 3D model of objects that can be created using various technologies, such as laser scanning, 3D modeling methods (e.g., CAD and BIM systems), photogrammetry, as well as data from drones and IoT sensors (Kumar, 2024).

2. Analysis of the condition of remediation objects. These models can be used for real-time analysis of the object's condition, such as checking the structural integrity of a bridge, assessing its wear, or predicting potential failure. The 3D analysis can include the evaluation of load-bearing, vibration, and other factors affecting the operational properties of the object (Xu et all., 2024).

3. Simulations and optimization of reconstruction and remediation processes. Based on 3D models, Digital Twins allow for the simulation of various scenarios, such as the impact of weather conditions, natural phenomena, seismic loads, or other external impacts. This helps to identify optimized design, technical, and economic solutions for the implementation of the remediation strategy (Gupta, Iyer, Kumar, 2024; Gaoet all., 2024).

JUSTIFICATION OF THE “DIGITAL RECONSTRUCTOR” PROJECT

Project Initiators: Representatives of the scientific community and the Ministry of Infrastructure of Ukraine.

The “Digital Reconstructor” project aims to leverage advanced digital technologies, specifically Digital Twin (DT) technology, to accelerate the recovery and remediation of war-affected territories in Ukraine. This project involves collaboration between academic institutions, design centers, geospatial companies, IT firms, and international partners to develop and implement innovative solutions for rapid post-conflict restoration of Ukraine.

Main Objective: The primary objective of the project is to enhance the efficiency, speed, and sustainability of post-war recovery by integrating Digital Twins into the management of infrastructure restoration and environmental remediation of territories affected by military activities.

Key Tasks:

1. Development of Digital Twins. Creating virtual models of war-damaged infrastructure (roads, bridges, buildings) and ecosystems (forests, water systems) using geospatial data, sensors, and real-time monitoring technologies.

2. Data Integration. Collecting and integrating real-time data from IoT devices, drones, and satellite imagery to ensure accurate and up-to-date digital analysis of the affected and needing restoration territories.

3. Optimization of Resource Allocation. Using Digital Twin models to optimize the allocation of resources (human, financial, and material) and ensure the most effective use of limited resources in the process of reconstruction and remediation (Xuet all., 2024).

4. Risk Assessment and Forecasting. Developing predictive models to assess the risks of future various threats of anthropogenic and other nature, which will help create more resilient systems for future development (Gao et all., 2024).

5. Public Engagement and Collaboration. Motivating cooperation between the public and private sectors, including international collaboration, to gain mutual benefits, including knowledge exchange, best practices, and attracting additional expertise to the process of recovery and revitalization of Ukraine.

Potential Benefits:

1. Accelerated Recovery. Digital Twins will significantly speed up the recovery process by providing real-time data for effective management decisions and efficient allocation of existing resources.

2. Improved Resilience. By modeling different scenarios and optimizing the design of remediation objects, the project will help create more resilient systems capable of withstanding future disasters.

3. Cost Reduction. The implementation of Digital Twins and the use of virtual models for monitoring the overall situation can minimize costly mistakes and optimize the design and construction timelines, as well as the use of optimal technologies and materials, ultimately leading to substantial savings.

4. Sustainable Development. It should be emphasized that the application of Digital Twins not only focuses on the physical restoration of damaged infrastructure but also on ecological remediation. In most cases, a Digital Twin refers to the modeling of physical objects and systems, but within the ecosystem, it can be used to model the impact of pollutants on natural objects and optimize the cleanup process. In this case, Digital Twins do not create an exact biological model of an ecosystem but can assist in planning effective ecological remediation, taking into account the impact of pollutants on ecosystems, which will help Ukraine achieve its sustainable development goals in the long term.

5. Global Knowledge Exchange. Cooperation with international platforms, such as the Global Infrastructure Facility (GIF) and the Global Digital Twin Network (GDTN), can provide access to the latest digital technologies and best practices in post-disaster remediation, creating a valuable knowledge exchange for post-war recovery and long-term resilience building (Pasupuleti, 2024).

Strategic Partnerships:

Ukrainian Universities and Design Centers will provide expertise in civil engineering and urban planning to ensure the realism and scalability of digital models for the remediation of affected territories.

Geospatial Companies and Consulting Firms, as the authors believe, will play a key role in developing accurate maps and virtual models of war-affected territories, providing valuable geospatial analysis using GIS and remote sensing technologies.

IT Companies and Startups, such as DataRobot, Accenture, and PwC, will provide advanced digital solutions, artificial intelligence, and data analytics capabilities to process large datasets, develop predictive models, and implement AI-driven tools for resource allocation.

International Partnerships with organizations such as the Global Infrastructure Facility (GIF) and the Global Digital Twin Network (GDTN) will help with the implementation of best practices, access to international experience, and technical support.

DISCUSSION

We can fully assert that Digital Twins are one of the promising tools for simulation modeling, with their scope of application potentially expanding in the field of crisis management in the context of mitigating the consequences of military activities and remediation. While simulation modeling is used to create models and predict their behavior, Digital Twins serve as living, constantly updating models that use real-world data for this purpose. Digital Twins not only allow for modeling but also effectively “reflect” the current state of a system in real time, making them a powerful tool for simulation, analysis, and forecasting (Bibri et all., 2024;).

Along with this, the question of how to effectively integrate Digital Twin technologies into crisis management processes and how feasible this will be in terms of resources and time is a subject of discussion. In this context, questions regarding the complexity and cost of such integration, as well as how effective the use of these technologies will be in different conditions and at various stages of remediation, present a promising direction for the authors' future research (Wang et all., 2023).

CONCLUSION

All of the above allows us to draw conclusions about the potential opportunities and advantages of applying Digital Twins in the processes of post-war reconstruction and remediation of socio-economic and ecological systems. By implementing advanced digital technologies into the national remediation strategy, Ukraine will be able to restore affected territories more quickly, efficiently, and with a greater emphasis on sustainability and durability, ensuring future generations a stronger and more adaptive infrastructure. This project represents a step towards the modernization of Ukraine as a whole, transforming it into an innovation-driven and investment-oriented country in the field of implementing progressive developments, technologies, and innovative solutions, thereby ensuring its revival and prosperity in the future.

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