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AN ENVIRONMENTALLY SUSTAINABLE APPROACH TO DEMOLITION WASTE IN THE RECONSTRUCTION PROCESS OF UKRAINE

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The current stage of Ukraine's development is characterized by the simultaneous combination of two large-scale processes – overcoming the consequences of war destruction and forming the foundations of long-term sustainable development. The destruction of residential buildings, industrial facilities, transport and engineering infrastructure has led to the formation of extremely large volumes of destruction waste, which significantly exceed the indicators typical for peacetime. By their nature, this waste is heterogeneous, which complicates their accounting, control and safe handling in conditions of limited resources and damaged infrastructure.

The problem of waste management is becoming particularly urgent due to the environmental risks associated with their uncontrolled accumulation and disposal. Soil and water pollution, dust emissions, release of heavy metals, asbestos and other hazardous substances pose threats to public health and ecosystem functioning. In many cases, these risks are cumulative and long-term in nature, which can negatively affect the restoration of territories in the future.

At the same time, the reconstruction of the country requires significant amounts of construction materials and energy resources, access to which is limited during the war and post-war periods. Under such conditions, destruction waste can be considered not only as an environmental problem, but also as a potential resource capable of reducing the burden on natural resources, reducing greenhouse gas emissions, and increasing the resource efficiency of reconstruction processes.

The transition to sustainable development and a circular economy opens up opportunities to integrate reuse, recycling, and recovery of materials into waste management. This approach combines environmental safety with economic feasibility and social responsibility, which is especially important in the context of rebuilding devastated communities.

The article examines the environmental and economic aspects of handling construction waste (CDW) in the post-war reconstruction of Ukraine. A quantitative assessment of the potential for its recycling is carried out based on scenario analysis. It is established that recycling 60% of CDW allows reducing CO_2 emissions by more than 1.5 million tons and providing an economic effect of more than €240 million. The need to integrate digital technologies and circular economy principles into the construction waste management system is substantiated. *Key words:* sustainable development, environmental management, demolition waste, CDW, circular economy, post-war reconstruction, waste management.

Екологічно сталий підхід до відходів руйнації в процесі відбудови України. Сорочинська О.Л.

Сучасний етап розвитку України характеризується одночасним поєднанням двох масштабних процесів – подолання наслідків воєнних руйнувань та формування основ довгострокового сталого розвитку. Руйнування житлових будинків, промислових об'єктів, транспортної й інженерної інфраструктури призвели до утворення надзвичайно великих обсягів відходів руйнації, які суттєво перевищують типові для мирного часу показники. За своєю природою ці відходи є неоднорідними, що ускладнює їх облік, контроль і безпечне поводження в умовах обмежених ресурсів та пошкодженої інфраструктури.

Проблема управління відходами руйнації набуває особливої актуальності з огляду на екологічні ризики, пов'язані з їх неконтрольованим накопиченням і захороненням. Забруднення ґрунтів і водних ресурсів, поширення пилу, вивільнення важких металів, азбесту та інших небезпечних речовин створюють загрози для здоров'я населення та функціонування екосистем. У багатьох випадках ці ризики мають кумулятивний і довготривалий характер, що може негативно впливати на відновлення територій у майбутньому.

Водночас відбудова країни потребує значних обсягів будівельних матеріалів і енергетичних ресурсів, доступ до яких у воєнний та післявоєнний періоди є обмеженим. За таких умов відходи руйнації можуть розглядатися не лише як екологічна проблема, а і як потенційний ресурс, здатний зменшити навантаження на природні запаси, скоротити викиди парникових газів і підвищити ресурсну ефективність відбудовчих процесів.

Перехід до принципів сталого розвитку та циркулярної економіки відкриває можливості для інтеграції повторного використання, переробки та відновлення матеріалів у систему управління відходами. Такий підхід дозволяє поєднати екологічну безпеку з економічною доцільністю та соціальною відповідальністю, що є особливо важливим у контексті відновлення зруйнованих громад.

У статті досліджено екологічні та економічні аспекти поводження з відходами руйнації (CDW) в умовах післявоєнної відбудови України. Проведено кількісну оцінку потенціалу їх переробки на основі сценарного аналізу. Встановлено, що переробка 60 % CDW дозволяє скоротити викиди CO_2 на понад 1,5 млн тонн та забезпечити економічний ефект понад 240 млн €. Обґрунтовано необхідність інтеграції цифрових технологій і принципів циркулярної економіки у систему управління відходами руйнації. *Ключові слова:* сталий розвиток, екологічний менеджмент, відходи руйнації, CDW, циркулярна економіка, післявоєнна відбудова, управління відходами.

Statement of the problem. The full-scale armed aggression has caused significant destruction of infrastructure and the formation of large-scale flows of destruction waste. According to the international assessment RDNA3, conducted with the participation of the World Bank, the European Commission and the United Nations, their volume exceeds 10–13 million tons [1]. The accumulation of such waste creates a significant environmental burden and requires the formation of a systematic approach to its processing.

The existing waste management systems in Ukraine were designed for peacetime and are not prepared for such extraordinary loads. Much of the infrastructure for processing, sorting and safe storage is damaged or destroyed, and the regulatory framework has limited mechanisms for controlling the management of hazardous waste components. This leads to chaotic accumulation and disposal of waste, which increases the risks of soil, water and air pollution, and creates new threats to public health.

The situation is complicated by the fact that, simultaneously with the accumulation of waste, there is an urgent need to quickly rebuild settlements, provide housing and basic services to millions of citizens affected by the war. The challenges are twofold: the need to quickly restore the housing and industrial stock and environmentally safe handling of millions of tons of construction waste. At the same time, demolition waste can become a valuable resource for secondary use in construction, infrastructure restoration and reducing the burden on natural resources, if the principles of the circular economy are applied.

Thus, the problem of destruction waste management in Ukraine is complex and simultaneously includes issues of environmental safety, resource conservation, technological efficiency, and regulatory regulation. Its solution is a key prerequisite for ensuring sustainable and safe reconstruction of destroyed territories and the formation of long-term environmental and economic stability in the country.

Relevance of the study. The current stage of Ukraine's recovery after large-scale destruction requires a comprehensive and systematic approach to the management of demolition waste, since the efficiency of their use directly affects the environmental safety, pace and quality of reconstruction of territories. The accumulation of millions of tons of construction and demolition materials overloads the existing waste management infrastructure and reveals the limitations of regulatory mechanisms for controlling hazardous components, which increases the risks of environmental pollution and threats to public health. At the same time, demolition waste, subject to the implementation of modern sorting, recycling and reuse strategies, can become an important resource for infrastructure recovery, contributing to reducing the burden on natural resources, reducing landfill volumes and reducing greenhouse gas emissions in accordance with the principles of sustainable development.

The relevance of the study is also determined by the need to adapt international experience of post-war reconstruction to Ukrainian conditions, taking into account the principles of the circular economy and integrating innovative technologies for material flow management. This includes the use of building information modeling (BIM), modular production of building components, mobile and stationary sorting and recycling systems, as well as measures to ensure the safe management of hazardous waste.

The creation of an effective system of sustainable management of demolition waste will simultaneously ensure rapid infrastructure restoration, minimize negative environmental impacts, and ensure the long-term sustainability of Ukrainian communities. Thus, research into the environmental aspects of demolition waste management is extremely relevant for the scientific substantiation of reconstruction strategies, the formation of effective technological and management solutions, and the integration of environmental safety, economic feasibility, and social responsibility into the country's reconstruction processes.

The connection of the author's work with important scientific and practical tasks. The author's work in the study "Environmentally sustainable approach to destruction waste in the process of reconstruction of Ukraine" is aimed at improving scientific methods of analysis and classification of construction waste, as well as developing approaches to their effective processing and minimizing negative impact on the environment. The work contributes to the development of a systemic and environmentally oriented approach to waste management in post-conflict conditions.

Analysis of recent research and publications. The issue of construction and demolition waste (CDW) management is the subject of active scientific research in the world, combining environmental, technological and socio-economic aspects. Particular attention is paid to the issues of integrating the principles of the circular economy, assessing environmental risks and developing effective sorting and recycling technologies to ensure sustainable development and minimize negative environmental impacts.

A review by J. Zuo et al. [2] provides a detailed analysis of global approaches to CDW management, highlighting that traditional methods of disposal and disposal do not meet the requirements of modern environmentally sustainable development. The authors point to the need to implement digital solutions, material life cycle modeling, and comprehensive sorting strategies that can reduce waste volumes, their environmental impact, and increase resource conservation potential.

The study by M. Osmani [3] highlights the importance of building information modeling (BIM) and automated CDW accounting systems as key tools for effective waste management during construction and renovation phases. Digital technologies allow for optimization of sorting, prediction of waste generation, and planning of material reuse.

In the context of sustainable construction, Kibert C. [4] refers to the concept of ecologically balanced design, where the transition to cyclical material management is a key component. Without considering the life cycle of building materials, it is impossible to achieve a low ecological footprint and high resource efficiency of land regeneration.

An analysis of the post-conflict specificity of CDW is considered in the work of Di Maria et al. [5], where it is noted that waste from destruction has an unstable composition and increased risks of toxicity, which complicates its environmentally safe management. H. Yuan et al. [6] in turn propose combined approaches (mechanical processing combined with chemical neutralization) to reduce the risks of soil and water pollution.

Among Ukrainian scholars, V. Biletskyi et al. [7] explore the potential of applying circular economy principles in CDW management in Ukraine, emphasizing that the reuse of construction materials can reduce the need for primary resources and reduce the negative impact on the environment. N. Kovalchuk and I. Hnatyuk [8] analyze the regulatory framework of Ukraine and identify gaps that complicate the implementation of modern sorting and recycling practices. L. Petrenko [9] emphasizes the need for digital monitoring of waste streams in large cities, M. Shevchuk et al. [10] investigate environmental risks associated with asbestos, heavy metals and other toxic impurities in CDW.

In recent years, the topic of CDW in Ukraine has received a new impetus due to military operations. A comprehensive study by O. Safranov, V. Prykhodko and A. Mykhailenko [11] is devoted to the characteristics of demolition waste management. In their work, O. Martsynyuk and O. Khandogina [12] extended these results by analyzing the heterogeneous composition of the waste and hazardous components, emphasizing the lack of technical and institutional support for effective management.

A. Hanoshenko's review [13] highlights the environmental impact of military operations and disruption of waste management infrastructure. S. Palii [14] examines the environmental aspects of building materials recycling with a focus on the reuse of secondary raw materials. T. Ivanova, D. Martynenko and Y. Kushnir [15] explore methods for optimizing dismantling and reuse of materials within the framework of a circular economy. Legal aspects and access to information on military waste are analyzed by A. Gafurova and M. Novak and O. Potip, emphasizing the need to improve the regulatory framework [16-17].

Highlighting previously unresolved parts of the general problem, to which this article is devoted. Despite existing research on demolition waste management, a number of aspects remain insufficiently studied. In particular, there are no systematic approaches to integrating environmentally sustainable demolition waste processing technologies into post-conflict reconstruction processes. Also, methods for assessing the impact of various disposal methods on the environment and the economic efficiency of reconstruction projects are insufficiently developed.

The article is devoted to the study of these unresolved issues. The author proposes methodological approaches and practical solutions that allow filling the gaps in knowledge regarding the classification, processing and reuse of demolition waste, as well as their integration into the sustainable process of restoring Ukraine's infrastructure.

The novelty lies in the development of a comprehensive environmentally sustainable approach to the management of demolition waste in the context of the reconstruction of Ukraine, which combines methods of classification, processing and reuse of construction materials. The integration of environmental and economic criteria into the decision-making process on waste disposal, which has not been systematically studied before, is proposed. The practical novelty is manifested in the creation of recommendations and models for organizations engaged in infrastructure reconstruction on the implementation of sustainable waste management technologies. This allows to increase the efficiency of construction processes, minimize the negative impact on the environment and promote the sustainable development of post-conflict territories.

Presentation of the main material. Based on generalized analytical assessments of international environmental organizations and expert reviews of the consequences of military destruction in Ukraine, the volume of waste from demolition and damage to infrastructure is estimated at 10–13 million tons per year, depending on the intensity of hostilities and the scale of destruction (Fig. 1). These figures are comparable to the average annual volume of solid household waste generation in peacetime, which indicates a critical increase in the load on the waste management system [1].

As can be seen from Figure 1, during 2022–2025, there is a rapid growth in the volume of demolition waste: from a negligible level in 2022 to over 12 million tons in 2025.

Such an increase in the volume of construction and demolition waste creates a complex of environmental, social and economic challenges. These include the risks of soil and water pollution, landfill overload, the need to create mobile sorting and recycling points, as well as the need to integrate the principles of the circular economy into the processes of post-war reconstruction. In these conditions, the formation of a systematic, environmentally friendly model of destruction waste management, capable of ensuring resource efficiency and environmental safety of the sustainable recovery of Ukraine, becomes particularly relevant.

According to data as of early 2024 (Fig. 2), as a result of the hostilities in the Russian Federation, more than 50% of the housing stock in a significant number of cit-

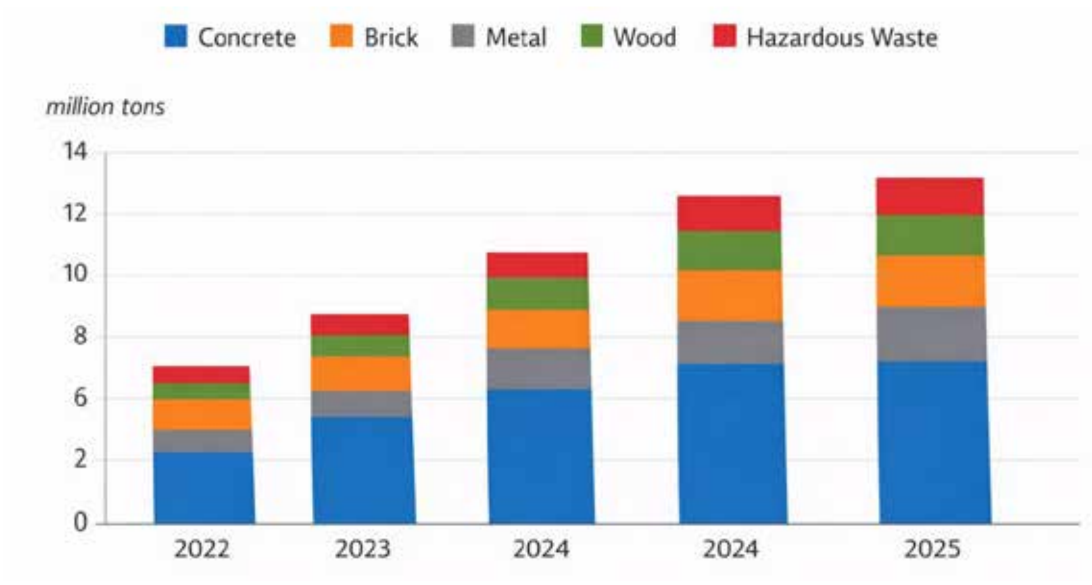

Fig. 1.Dynamics of construction and demolition waste in Ukraine (2022-2025)

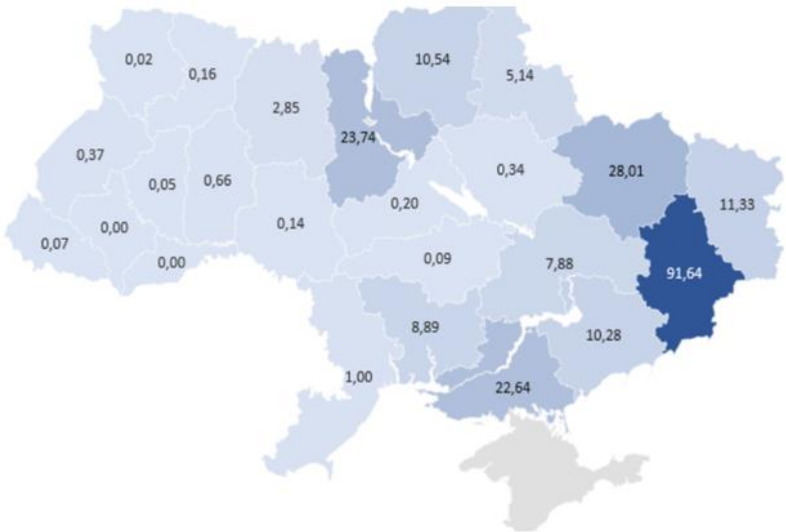

Fig. 2. Regional distribution of the number of destroyed or damaged housing stock, thousand units [18]

ies and towns has been damaged or destroyed [18]. This requires not only the restoration of individual buildings, but also the comprehensive restoration of cities, the development of new urban planning documentation, and other measures.

In post-conflict situations, numerous problems have been identified in the management of construction waste generated by the destruction of infrastructure. This waste is potentially hazardous, as it contains chemical residues, unexploded ordnance (UXO), heavy metals, and asbestos, which pose a serious threat to human health and the environment. The presence of such components complicates the process of waste collection, transportation, and recycling, and failure to comply with safety measures can lead to acute and chronic poisoning, as well as man-made accidents [19-20].

The situation is made worse by the fact that much of the existing waste management infrastructure has been damaged or completely destroyed as a result of the fighting. This limits the state's ability to effectively process and recycle construction and hazardous waste during and after the conflict. The absence or reduced functionality of landfills, sorting stations, and processing plants leads to the accumulation of hazardous waste in cities and villages, which threatens public health and leads to long-term environmental consequences.

At the same time, the post-war period offers unique opportunities for creating a more reliable, safe and sustainable waste management system. It allows for the introduction of modern sorting and recycling technologies, including methods for the disposal of hazardous components and the conversion of construction waste into secondary resources. Focusing on the principles of the circular economy allows not only to reduce the negative impact on the environment, but also to increase the efficiency of the use of material resources, stimulating the economic recovery of territories affected by the conflict.

The study reviewed international experience in managing construction waste in post-conflict settings. The experience of Syria shows that complete demolition and construction of new structures is not always cost-effective. An environmentally sound and feasible measure is to repair buildings that have retained their structural integrity but have been damaged by detonation [21]. The efforts of the United Nations Environment Programme (UNEP) to rebuild Iraq and Lebanon demonstrate the importance of prior structural assessment of buildings, global cooperation on waste management, and the use of recycled materials during reconstruction [22]. Thus, a strategy for reusing materials, minimizing demolition, and reducing construction waste is critical for sustainable and safe infrastructure reconstruction.

Effective construction waste management (CDW) is not only a logistical requirement, it is essential for sustainable recovery. Recycling and reuse of construction materials can reduce landfill use, protect natural resources, and reduce greenhouse gas emissions from raw material extraction and transportation. Early implementation of recycling strategies during the design and planning of reconstruction can improve cost-effectiveness and environmental impact [23].

For effective management of demolition waste, it is important to integrate three key strategies:

1. Waste reduction at source – implementation of modern design and construction methods, such as building information modeling (BIM), modular and precision manufacturing, which allows minimizing waste generation at the construction stage.

2. Material reuse – selection and certification of building components for secondary use, implementation of regulatory mechanisms that stimulate the market for recycled materials.

3. Development of recycling infrastructure – application of mobile and stationary sorting technologies, mechanical and chemical processing of materials (concrete, steel, phosphogypsum composites), creation of local markets for secondary resources.

These strategies form the basis for developing and comparing scenarios for waste management at different levels of technology, recycling and reuse. To substantiate such scenarios, a quantitative assessment of the total volume of waste is required, which allows for the identification of the potential for landfill reduction, the need for recycling capacity and the possible environmental impact.

According to estimates from the International Assessment of Damage and Recovery Needs for Ukraine (RDNA3), conducted with the participation of the World Bank, the European Commission, and the United Nations, the total volume of demolition waste exceeds 10–13 million tons.

For quantitative analysis, we will assume an average value of 12 million tons of CDW.

Based on generalized European studies, the structure of CDW can be presented as follows (see Table 1):

In order to substantiate the environmental and economic feasibility of processing demolition waste, a scenario analysis of two alternative models was conducted: full disposal and partial processing (60%).

Scenario 1 – 100% landfilling: Assuming full landfilling of 12 million tonnes of CDW, CO_2 emissions from waste transportation and disposal average 18–25 kg CO_2 per tonne. An average value of 22 kg CO_2/t was used for the calculations.

The total emissions are defined as: 12 million tons × 22 kg ≈ 264 thousand tons of CO_2.

The financial costs of disposal (at an average cost of €8–12/t) will be approximately: 12 million t × €10 ≈ €120 million.

Thus, the linear "demolition–disposal" model is accompanied by both significant climate impacts and direct budgetary costs.

Scenario 2 – Recycling 60% of CDW: The alternative scenario involves recycling 60% of the total waste, equivalent to approximately 7.2 million tonnes. This would involve recycling: 70% concrete, 80% metal, 50% brick, 40% wood.

Processing 6.6 million tons of concrete allows for the production of about 4.6 million tons of secondary crushed stone, which reduces the need for the extraction of natural materials by a similar amount.

In addition to the resource effect, there is a significant reduction in CO_2 emissions:

Table 1

Structure of destruction waste by type of materials and their volume, million tons

Component	Fraction, %	Estimated volume, million tons
Concrete and reinforced concrete	55 %	6,6
Brick and ceramics	20 %	2,4
Metal	10 %	1,2
Wood	8 %	0,96
Other materials	7 %	0,84

• concrete recycling provides a reduction of approximately 15 kg of CO_2 per 1

ton, which in total amounts to about 69 thousand tons of CO_2;

• metal recycling allows for a reduction of up to 1.5 tons of CO_2 per 1 ton,

which is equivalent to approximately 1.5 million tons of CO_2.

The total emission reduction potential is about 1.57 million tons of CO_2, which is six times higher than the full disposal scenario.

Additional economic results are generated through the sale of secondary materials:

• secondary crushed stone (7–12 €/t): 4.6 million t × 9 € ≈ 41 million €;

• scrap metal (150–250 €/t): 1 million t × 200 € ≈ 200 million €.

The total potential economic impact exceeds €240 million, significantly exceeding the costs of disposal.

To quantitatively compare the considered scenarios for the management of demolition waste, a generalized technical, economic and environmental analysis was performed, taking into account CO_2 emission indicators, the volume of natural resource involvement and financial results. The obtained calculations allow us to assess the cumulative effect of the transition from the scenario of preferential disposal to the scenario with a high share of recycling, as well as to clearly demonstrate the potential benefits of implementing the principles of the circular economy. The results of the comparative analysis are presented in Table 2.

The calculations obtained show that even partial recycling of 60% of demolition waste allows:

• to reduce CO_2 emissions by more than 6 times compared to landfilling;

• to reduce the load on natural quarries;

• to provide an economic effect;

• to form a domestic market for secondary construction materials.

Thus, the implementation of an environmentally sustainable approach to the management of demolition waste is not only environmentally appropriate, but also an economically sound direction for the post-war reconstruction of Ukraine.

Effective CDW management involves the implementation of BIM modeling, digital material registers and waste stream monitoring systems. This allows for optimization of dismantling, minimizing resource losses and ensuring traceability of materials throughout the life cycle. Figure 3 shows how digital tools, including building information modeling (BIM), modular manufacturing and material tracking systems, are integrated into CDW management processes, optimizing the collection, sorting and reuse of construction materials.

Digital technologies allow for life cycle analysis of materials, planning for component reuse, and ensuring transparency at all stages of waste management. This helps minimize waste generation and increase the efficiency of post-war reconstruction.

Digital tools are key to reducing waste and tracking materials. Systems such as BIM help improve life cycle analysis and resource efficiency, while modular construction allows components to be manufactured in factories, minimizing on-site waste and speeding up the renovation process [24-25].

For effective management of construction waste (CDW), it is important to understand the composition of the materials and their environmental risks. Table 3 summarizes the main components of CDW, potential environmental risks, and reuse options.

As Table 3 shows, most construction materials can pose a serious threat to the environment if mishandled, but at the same time there are real opportunities for their reuse and recycling. In particular, concrete and brick can be used as secondary aggregates, metal for the production of secondary steel, and wood for fuel or composting purposes. In the case of hazardous components such as asbestos or chemical residues, specialized disposal and neutralization methods are required.

Hazardous crushed construction waste (bricks, cement, mortars) can be used not only for construction materials. The simplest use is as a fill for roads and paths or as backfill for excavations that require compaction after filling.

In summary, the analysis of international practices, technological innovations and experience in managing demolition waste during the post-crisis reconstruction period indicates the real possibility of forming a sustainable and systemic reconstruction model in Ukraine. Provided that the principles of the circular economy are consistently integrated, the recycling infrastructure is developed and responsible management decisions in the field of waste management are implemented, the country has the potential to ensure a flexible, comprehensive and environmentally friendly reconstruction.

Main conclusions. It was established that the scale of destruction waste generation in Ukraine creates a significant environmental burden and requires

Table 2

Comparison of CDW handling scenarios

Indicator	waste disposal	Processing 60 %
CO_2 emissions	264 thousand tons	–1,57 million tons
Use of natural resources	100 %	–4,6 million tons
Financial result	–120 million €	+240 million €

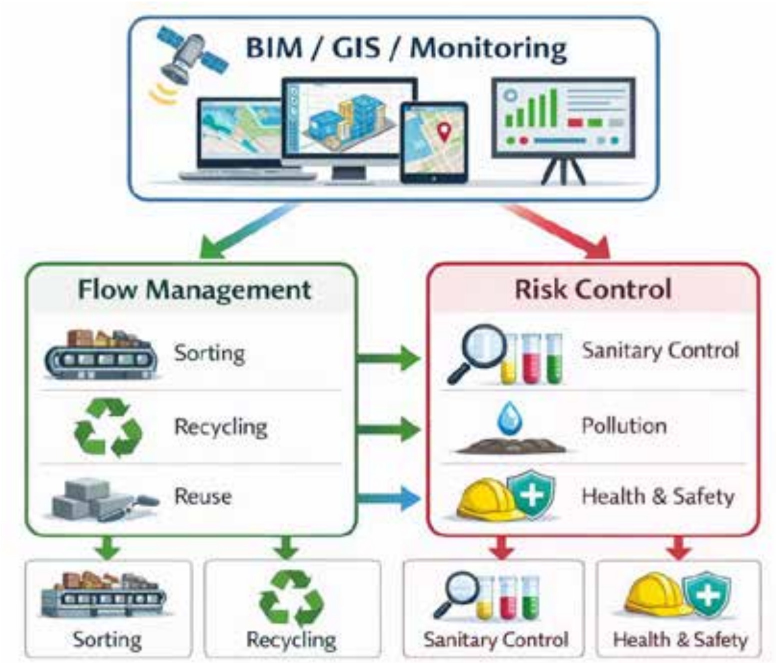

Fig. 3. Integrating digital technologies in CDW management

Table 3

CDW main components and environmental risks

Component	Risks	Potential use
Concrete	Soil pollution	Secondary crushed stone
Brick	Dust, heavy metals	Fillers
Metal	Corrosion, toxic compounds	Recycling, secondary steel
Wood	Dust, rot	Fuel, compost
Asbestos	Carcinogenic fumes	Specialized disposal
Chemical residues	Toxicity, water pollution	Special neutralization methods

a transition from a linear management model to a circular material recycling system. The scenario analysis demonstrated the environmental inefficiency of complete waste disposal, which is accompanied by high greenhouse gas emissions and significant financial costs.

It is substantiated that recycling 60% of demolition waste provides a reduction in CO_2 emissions by more than 1.5 million tons, a reduction in the use of natural resources and a positive economic effect. The feasibility of integrating digital technologies, such as BIM modeling, digital material registers and flow monitoring systems, into the CDW management system to increase the efficiency and transparency of reconstruction processes is proven.

It is confirmed that an environmentally sustainable approach to the management of demolition waste is a strategically important element of the post-war reconstruction of Ukraine and is consistent with the principles of the circular economy. The proposed quantitative approach can be used in the development of state and regional programs for the management of demolition waste.

Prospects for using the research results. The research results can be used to develop strategies for sustainable management of demolition waste and implement effective recycling technologies. This allows for increased environmental safety, rational use of secondary resources, and sustainable development of the infrastructure reconstruction processes in Ukraine.

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