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STRUCTURAL - TECHNOLOGICAL APPROACHES TO REINFORCED CONCRETE RECYCLING: INTEGRATION OF DESIGN, DECONSTRUCTION AND REUSE TECHNOLOGIES

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Abstract. The transition from a linear to a circular economy has become a defining paradigm in the modern construction sector, particularly in the context of reinforced concrete, which remains one of the most widely used structural materials worldwide. This study focuses on structural-technological approaches to reinforced concrete recycling through the integration of design, deconstruction, and reuse technologies. The construction industry is responsible for a significant share of global resource consumption and waste generation, which necessitates the development of comprehensive strategies aimed at closing material loops and reducing environmental impact.

The relevance of this research is especially high for Ukraine, where large-scale destruction caused by war has resulted in the accumulation of millions of tons of construction and demolition waste. Reinforced concrete debris represents both an environmental challenge and a valuable secondary resource for post-war reconstruction. Effective recycling and reuse strategies can significantly reduce the demand for primary raw materials, decrease greenhouse gas emissions, and accelerate recovery processes.

The proposed approach is based on the integration of key stages of the life cycle of reinforced concrete structures, including design for deconstruction, selective dismantling, material recovery, and reuse. Design strategies oriented toward future disassembly enable the preservation of structural elements and increase their potential for repeated application. Selective deconstruction technologies, as opposed to traditional demolition, ensure higher quality material streams and minimize losses. The development of recycling infrastructure is identified as a critical factor that determines the feasibility of transforming concrete waste into high-quality secondary aggregates or reusable structural components.

A central role in this framework is assigned to digital technologies, which connect all stages of the material life cycle.

Building information modelling and digital material passports enable traceability of structural elements, improve decision-making processes, and support the evaluation of environmental and economic performance. These tools create an integrated information environment that enhances the efficiency of reuse and recycling strategies.

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In addition, the study emphasizes the importance of regulatory and economic mechanisms as enabling conditions for the implementation of circular practices. Without appropriate legal frameworks, financial incentives, and market structures, even advanced technological solutions cannot be effectively applied at scale.

The results demonstrate that the integration of design, deconstruction, and reuse technologies within a structural-technological framework provides a viable pathway toward circular construction. For Ukraine, this approach offers not only alignment with global sustainability trends but also a practical solution for transforming construction waste into a strategic resource for rebuilding infrastructure.

Keywords: sustainable development in construction; BIM-technologies; construction and demolition; reuse of reinforced concrete elements; life cycle assessment (LCA)

INTRODUCTION

The transition from a linear to a circular economy has become the defining paradigm of today's construction science and practice. As highlighted in recent systematic reviews and methodological frameworks-particularly studies on circular concrete reuse, life cycle assessment (LCA), and design for deconstruction (DfD) – the construction industry is increasingly recognized as both a major consumer of natural resources and a leading generator of waste. Reinforced concrete (RC), as one of the most widely used construction materials globally, plays a central role in this challenge. Contemporary research emphasizes that integrating design, deconstruction, and reuse technologies can significantly reduce environmental impact, extend material life cycles, and improve resource efficiency.

Globally, the construction sector accounts for approximately 35-40% of total material consumption and generates up to 30% of all solid waste. Traditional demolition practices, which prioritize speed over selectivity, result in the downcycling of concrete into low-grade aggregates or, worse, landfill disposal. However, recent studies demonstrate that up to 90-95% of reinforced concrete elements can be technically suitable for reuse if appropriate design and deconstruction strategies are implemented. This has led to the emergence of structural-technological approaches that integrate circular principles at every stage of a building’s life cycle – from initial design to end-of-life processing.

The concept of Design for Deconstruction (DfD) is particularly important in this context. It involves planning buildings in such a way that their components can be easily dismantled, recovered, and reused. When combined with digital tools such as Building Information Modeling (BIM) and material passports, DfD enables accurate tracking of material properties and facilitates future reuse. Furthermore, probabilistic performance-based design approaches allow engineers to predict the durability and residual capacity of reinforced concrete elements, making it possible to safely integrate reused components into new structures.

While these approaches are gaining traction globally, their relevance is especially acute in Ukraine. As a result of the ongoing war, vast quantities of construction and demolition waste have been generated due to the destruction of residential, industrial, and infrastructure facilities. Millions of tons of reinforced concrete debris now represent both an environmental burden and a potential resource. The accumulation of such waste poses serious risks, including land contamination, air pollution from dust, and inefficient land use. At the same time, Ukraine faces an urgent need for reconstruction, which requires enormous volumes of construction materials.

In this context, the implementation of circular economy principles is not merely an environmental initiative but a strategic necessity. The recycling and reuse of construction waste can significantly reduce the demand for virgin raw materials, lower greenhouse gas emissions, and accelerate reconstruction efforts. Moreover, it creates opportunities for the development of new industries and technologies within the country.

PURPOSE AND METHODS

To address the challenge of construction waste management in Ukraine, several key pathways can be identified:

First, the establishment of systematic sorting and classification processes is essential. Construction debris must be separated into categories such as reinforced concrete, steel, masonry, and hazardous materials. Advanced sorting technologies, including mobile crushing and screening units, can be deployed directly at demolition sites to improve efficiency and reduce transportation costs.

Second, the adoption of selective deconstruction techniques should replace conventional demolition methods. This involves carefully dismantling structures to preserve the integrity of reusable components. Techniques such as diamond wire cutting, hydraulic separation, and modular disassembly can significantly increase the recovery rate of high-quality materials.

Third, the development of recycling infrastructure is critical. Recycled concrete can be processed into aggregates for use in new concrete production, road construction, and other applications. At the same time, research and pilot projects should focus on the direct reuse of structural elements, such as beams, slabs, and columns, which retain sufficient load-bearing capacity.

Fourth, the integration of digital technologies can enhance the efficiency of the entire process. BIM-based material databases and digital passports can store information about the composition, strength, and history of structural elements, facilitating their reuse in future projects.

Finally, regulatory and economic mechanisms must support the transition to circular practices. This includes the development of standards for recycled materials, incentives for reuse, and policies that prioritize sustainable construction methods in public procurement.

In conclusion, the adoption of structural-technological approaches to reinforced concrete recycling represents a crucial step toward sustainable development in the construction industry. For Ukraine, this transition is not only aligned with global trends but also provides a practical solution to the unprecedented challenges posed by war-related destruction. By integrating design, deconstruction, and reuse technologies, it is possible to transform construction waste from a problem into a valuable resource, supporting both environmental protection and national recovery.

RESULTS AND EXPLANATIONS

Principle 1 – Establishment of an Efficient System for Sorting and Classification of Construction Waste.

The first principle of the structural-technological approach to transforming Ukraine's construction sector under circular economy conditions is the formation of an effective system for sorting and classification of construction and demolition waste. The relevance of this principle is strongly supported by contemporary European research and analytical reports. According to the European Commission, construction and demolition waste accounts for more than one third of all waste generated in the EU, reaching approximately 40% of the total volume, as confirmed by both baseline statistical data and updated studies of the EU Joint Research Centre for 2024-2026 (*Report to the European Commission, Construction and demolition waste, Techno-economic and environmental assessment of construction and demolition waste management in the European Union*). Current assessments indicate that around 83% of this waste stream can potentially be prepared for reuse or recycling, making sorting systems a key enabler of circular economy implementation. Importantly, these data are considered highly relevant as they are based on 2024 reports and updated EU policy recommendations for 2026 aimed at achieving climate neutrality.

Modern European practice demonstrates that the efficiency of sorting is directly determined by the combination of regulatory frameworks and technological solutions. The EU Waste Framework Directive identifies construction waste as a priority stream and emphasizes the necessity of selective demolition, as mixed waste often contains hazardous components such as asbestos or chemical additives, which complicate recycling and reduce the quality of secondary raw materials (*Report to the EC)*. The advantage of this approach lies in ensuring high-quality secondary materials suitable for reuse in new construction; however, its implementation requires significant organizational restructuring and financial investment, which creates barriers for countries with transitional economies.

Germany provides an example of advanced automated sorting systems based on optical sensors and artificial intelligence. These systems enable the identification of complex multi-component waste streams and the separation of concrete, metals, gypsum, and polymers with high precision. This significantly improves the quality of recycled materials and reduces resource losses. At the same time, the main limitation of this approach is its high implementation cost and dependence on sophisticated technological infrastructure, which restricts scalability in countries with limited investment capacity.

An alternative model is implemented in the Netherlands and Northern European countries, where preference is given to on-site sorting directly at construction and demolition sites. This approach ensures high purity of material streams and preserves the structural integrity of components, which is critical for their subsequent reuse. However, this model requires highly qualified personnel and longer demolition times, which may affect the overall economic efficiency of projects.

Nevertheless, even in EU countries where formal recycling targets exceed 70%, a significant portion of waste is still subjected to so-called low-grade recycling, such as backfilling applications, which does not fully comply with circular economy principles [1]. This demonstrates that the quality of sorting, rather than only quantitative recycling rates, determines the true effectiveness of the system.

From a technological perspective, modern sorting systems include multi-stage processes such as primary separation of large elements, crushing, magnetic separation of reinforcement steel, and high-precision automated sorting. European Commission studies confirm that such integrated systems enable a transition from low-value utilization of concrete waste to its reintegration into new concrete production, which is significantly more efficient both environmentally and economically (*Report to the EC)*.

International experience further shows that the effectiveness of sorting systems strongly depends on the combination of strict regulatory frameworks and advanced technological solutions. Japan and Singapore represent the most illustrative examples of highly efficient global systems.

In Japan, the Construction Material Recycling Law enacted in 2000, which introduced mandatory requirements for sorting, selective demolition, and on-site processing of construction materials enabled the transition to efficient sorting and recycling. Contractors are required to separate waste streams such as concrete, asphalt, and wood, fundamentally transforming construction waste management practices [2]. As a result, Japan has achieved one of the highest recycling rates globally, with more than 95-99% of construction waste, particularly concrete and asphalt, being recycled [3]. The Japanese model offers significant advantages, as strict regulation ensures near-complete material recovery, minimizes illegal dumping, and establishes a stable secondary materials market. However, it requires strong administrative control, detailed planning already at the design stage, and substantial institutional capacity, which may limit its transferability to transitional economies.

Singapore represents another highly efficient and technologically integrated model. Under the Zero Waste Masterplan and regulations of the Building and Construction Authority, sorting and recycling of construction waste are mandatory components of construction projects. As a result, the recycling rate of concrete waste reaches approximately 99%, with materials widely reused in road construction and land reclamation projects. Additionally, the updated Green Mark certification system (2025) requires consideration of recycled material use and lifecycle carbon assessment, further reinforcing circular economy principles.

The Singaporean approach is characterized by strong integration of state policy, economic incentives, and technological solutions, enabling high efficiency and rapid scalability. However, its effectiveness is largely driven by centralized governance, strict regulatory enforcement, and limited land availability, which forces maximum resource efficiency but may limit adaptability in larger or decentralized countries.

Overall, the experiences of Japan and Singapore demonstrate that efficient sorting systems are achieved through mandatory source separation, integration of regulatory frameworks, and development of advanced recycling infrastructure. At the same time, these examples confirm that high performance is only possible under long-term policy consistency, sustained investment, and coordination among all stakeholders.

Thus, the establishment of an effective system for sorting and classification of construction waste is a fundamental prerequisite for implementing the structural-technological approach. This stage determines the quality of subsequent deconstruction, recycling, and reuse processes, forming the foundation for transitioning from a linear construction model to a closed-loop material system.

A positive domestic example in this area is the cooperation between the authorities of the city of Mykolaiv and the Japanese corporation IKEE Group Ltd, which has resulted in the launch of a pilot project for construction waste recycling. The project предусматриває the collection of demolition waste, including concrete, brick, and asphalt, followed by its sorting and processing for subsequent use as secondary raw materials in the restoration of road infrastructure. Since October 2024, a construction waste recycling line with a capacity of 100,000 tons per year has been operating in the city of Bila Tserkva with the support of the Japan International Cooperation Agency (JICA) (Fig. 1). The image is illustrative for security reasons.

Fig. 1. Model of a construction waste sorting and recycling line
Рис.1. Модель лінії сортування та переробки будівельних відходів

Principle 2 – Implementation of Selective deconstruction Technologies Instead of Traditional Demolition.

The second principle is the implementation of selective deconstruction technologies instead of traditional destructive demolition. In contemporary scientific literature, this approach is considered a key instrument for increasing the level of reuse of construction materials, particularly reinforced concrete structures, and for reducing the environmental burden associated with construction and demolition waste.

Recent studies show that construction waste management strategies significantly influence both the environmental and economic performance of a building's life cycle. In particular, Yazdanbakhsh [4] proposed a bi-level assessment framework for evaluating construction and demolition waste management strategies, emphasizing that selective deconstruction provides a significantly higher potential for material reuse compared to conventional demolition, although it requires higher initial costs and more complex process organization.

Comprehensive life cycle assessments of scenarios involving reuse and controlled deconstruction demonstrate a substantial reduction in natural resource consumption and CO_2 emissions compared to complete demolition and the production of new materials [5, 6]. These studies show that integrating reuse strategies into the life cycle of reinforced concrete structures is more effective than traditional recycling into secondary aggregates.

European research and practical experience have proven that the environmental effectiveness of selective deconstruction is closely linked to the quality of subsequent recycling processes. For example, the use of recycled coarse aggregate obtained through controlled demolition provides better life cycle environmental performance compared to conventional natural aggregates, especially when optimized logistics and minimized material contamination are ensured [7].

However, it should be noted that although selective deconstruction is environmentally more advantageous, its economic costs can be higher than those of traditional demolition, which creates a barrier to widespread implementation without governmental incentives. Similar conclusions are supported by economic assessments [8, 9], which indicate that without accounting for long-term environmental benefits, conventional demolition remains more financially attractive in the short term. At the same time, selective deconstruction can become economically competitive in the long term, particularly when structural elements are reused and the need for new materials is reduced [10].

Of particular importance for the modern concept of selective deconstruction are studies integrating BIM technologies and digital demolition planning models. For example, Kim and Kim [11] developed a BIM-based tool for assessing the deconstructability of buildings, enabling the evaluation of reuse potential already at the design stage. Similarly, Guerra et al. demonstrated that the use of 4D-BIM allows optimization of demolition planning and increases the reuse rate of concrete and drywall through accurate simulation of dismantling processes [12]. Japanese government policies on skyscraper disposal have fostered the development of an entire industry of dust-free and noiseless dismantling [13]. The technology involves the preliminary dismantling of all interior elements and non-load-bearing structures, followed by the step-by-step removal of all load-bearing structural components of the building under a protective enclosure, layer by layer. The building appears to "descend" downward, decreasing by one floor from the top (Fig. 2).

Fig. 2. Skyscraper demolition using the TEcoRep technology [13].
Рис.2. Знесення хмарочосів за технологією TEcoRep [13].

The practical effectiveness of selective deconstruction has also been demonstrated in experimental studies on reinforced concrete structures, showing that component reuse is technically feasible, although it requires a high level of workforce training and standardization of procedures [14, 15].

The case of Hanoi illustrates that the absence of systematic selective deconstruction leads to the mixing of waste streams and a significant reduction in recycling potential [16]. Similar challenges are observed in Middle Eastern countries, where insufficient levels of sorting and deconstruction significantly reduce the efficiency of construction waste management systems [17].

Thus, the synthesis of current scientific research allows us to conclude that selective deconstruction is a key element in the transition toward a circular construction model. Its main advantage lies in maximizing the preservation of the material value of structures, reducing environmental impact, and enabling the reuse of reinforced concrete elements. At the same time, the main limitations include higher initial costs, organizational complexity, and the need for digital support and regulatory frameworks.

Principle 3 – Development of Construction and Demolition Waste Recycling Infrastructure.

The third principle of the structural–technological approach toward a circular economy is the development of construction and demolition waste recycling infrastructure, particularly reinforced concrete waste, as a key element for closing material loops in the construction sector. In contemporary scientific literature, this stage is considered a critical link between deconstruction and material reuse, determining the actual effectiveness of the entire circular model.

Comprehensive life cycle assessments of construction materials demonstrate that the level of recycling infrastructure development is a decisive factor influencing the environmental benefits of concrete reuse. Even when there is high potential for structural reuse, the absence of adequate infrastructure significantly reduces the overall CO_2 emission reduction effect [6]. At the same time, an integrated recycling system ensures substantially higher efficiency of closed-loop material cycles. Similar conclusions are presented by Kim and Tae, who emphasize that infrastructure capacity for recycling is a key determinant of LCA results for concrete structures at a national scale [18].

European experience confirms that recycling construction and demolition waste into high-quality secondary materials is significantly more effective than simple landfilling or low-grade downcycling. Only a developed infrastructure allows the transition from reducing the quality of the material to real recycling while preserving its technical value, which is of fundamental importance for the circular economy [8].

At the same time, the economic efficiency of such systems depends strongly on the scale of recycling operations and the logistics of waste flow management.

Practical experience from Asian countries demonstrates different models of recycling infrastructure development. The case of Hong Kong shows that centralized concrete slurry treatment systems can significantly reduce waste volumes and enable its reuse in construction materials production, although they require high technological control and substantial investment in specialized facilities [19]. Such systems are highly efficient, but their limitation lies in dependence on centralized infrastructure and difficulties in scaling.

China provides another example, where the development of recycling plant networks has significantly reduced the carbon footprint of the construction sector, particularly in large urban agglomerations generating massive volumes of construction waste. However, uneven regional infrastructure development reduces overall system efficiency [14, 20]. This highlights a key issue of spatial imbalance, where advanced regions achieve high recycling rates, while less developed areas lag behind, weakening national performance indicators.

Similar challenges are observed in Middle Eastern cities such as Riyadh, where despite the existence of sustainability policies, insufficient recycling infrastructure leads to low utilization rates and a high proportion of landfilled construction waste. This demonstrates that regulatory frameworks alone are insufficient without corresponding physical infrastructure [17]. Economic studies further confirm that the viability of recycling systems depends directly on infrastructure scale and the stability of construction waste flows, as only large-scale systems achieve sufficient return on investment in recycling technologies [9]. This is particularly important for countries undergoing post-conflict reconstruction, where waste generation is high but infrastructure is initially limited.

Thus, synthesis of current research allows the conclusion that the development of recycling infrastructure is a critical third stage of the structural-technological approach to circular transformation in the construction sector. At this level, construction waste is effectively converted into secondary resources, markets for recycled materials are formed, and material loops are closed.

Principle 4 – Integration of Digital Technologies: BIM and Digital Material Passports.

The fourth principle is the integration of digital technologies, including Building Information Modelling (BIM) systems and digital material passports. This principle aims to ensure full traceability of construction materials and to create conditions for informed decision-making regarding reuse, recycling, and end-of-life scenarios for reinforced concrete structures. Today, digitalisation is a key enabling tool for circular construction systems, connecting design, deconstruction, and resource recovery into a unified system.

Life Cycle Assessment (LCA) supported by digital systems significantly improves the accuracy of evaluating the environmental impact of construction materials [21]. Methods for environmental assessment of concrete structures become considerably more reliable when structured digital data are used, enabling better-informed decisions both at the design stage and during building operation [19]. Modern approaches and software tools allow the analysis of construction material use at the end-of-life stage even before demolition occurs [22], and support the creation of digital material and component banks that store information about structural elements and enable their future reuse [23]. Guerra et al. demonstrate that the use of 4D-BIM significantly improves planning for construction waste reuse by simulating demolition sequences and identifying elements suitable for recovery [12]. This increases material recovery rates and reduces resource losses. However, the main limitation of this approach is its strong dependence on data quality and the need for continuous updating of digital models throughout the building lifecycle. In addition, BIM-based reuse assessment methods developed evaluate the potential and economic feasibility of reusing precast reinforced concrete elements at the urban system level [24, 25]. To facilitate reuse, digital models can already at the design stage improve future deconstruction processes by analysing graph-based deconstructability assessments [11] and demonstrating the technical feasibility of demountable reinforced concrete structures using dry connections [26].

However, certain limitations of digital integration should also be noted. Although BIM-based design-for-deconstruction approaches improve the environmental performance of buildings, their implementation requires significant initial investment in modelling, data collection, and coordination among project stakeholders [27]. Digital technologies are particularly relevant in the context of post-war reconstruction. Digital processes allow the transformation of construction debris into structurally suitable material by modeling and optimizing load-bearing systems, which opens up new possibilities for the reuse of the same concrete.

Overall, the integration of digital technologies represents the fourth key principle of the structural-technological approach. It ensures the connection between design, deconstruction, and recycling, forming a unified information-based system for managing material flows. International experience shows that BIM and digital material passports are essential prerequisites for implementing a circular construction model, and their adoption in Ukraine is critically important for efficient post-war reconstruction and minimization of construction resource losses.

Principle 5 – Renewal of the regulatory framework and economic support mechanisms.

The fifth principle involves updating and/or developing a new regulatory framework and establishing effective economic support mechanisms. This principle is considered a systemic instrument that ensures the implementation of all previous stages, since even the most advanced technological solutions in selective deconstruction, recycling, and reuse of reinforced concrete cannot be effectively applied without appropriate legal regulation, economic incentives, and market mechanisms.

The effectiveness of any system depends not only on technological innovation but also on the maturity of the institutional environment that governs material flows and end-of-life scenarios. Life cycle assessment (LCA) studies demonstrate that the environmental performance of construction and demolition waste management is highly dependent on regulatory conditions and economic incentives. National environmental assessment systems directly influence decision-making in the construction sector, as regulatory methodologies determine whether recycled concrete is treated as a resource or as waste with limited reuse potential [14]. Similarly, reuse and recycling scenarios lead to significant reductions in environmental impact only when supported by integrated policy and economic mechanisms that internalize environmental costs and promote closed material loops [9].

European experience shows that the combination of regulatory pressure and financial incentives is the most effective driver of circular transformation. The EU Waste Framework Directive sets mandatory recycling targets and introduces the principle of extended producer responsibility, partially shifting environmental costs to construction market stakeholders. Generalized assessments indicate that such policies have significantly increased recycling rates across EU countries, although differences remain due to varying levels of institutional capacity and infrastructure development. Economic evaluation models for waste management are critically important, as financial feasibility often determines the practical implementation of solutions [12]. However, a limitation is that even in Europe, economic incentives are not always sufficient to fully eliminate low-quality recycling practices, especially where landfilling remains a cheaper option.

In rapidly developing regions, particularly in Asia and the Middle East, regulatory and economic systems exhibit varying levels of maturity. Studies from China indicate that combining environmental policies with life cycle assessment tools can significantly reduce the carbon footprint of the construction sector, especially when secondary material markets are integrated into national planning [8, 20]. At the same time, regional disparities in policy implementation reduce overall system efficiency. In Hong Kong, for example, the management of concrete slurry waste demonstrates that strict regulation improves material recovery rates but involves high costs and dependence on centralized infrastructure.

In Gulf countries, particularly Saudi Arabia, life cycle assessments of construction waste management systems show that regulatory measures without economic incentives are insufficient to achieve high recycling rates [20]. Despite the presence of sustainability policies, weak market motivation and underdeveloped secondary material markets lead to the continued reliance on landfilling. This highlights a key limitation: regulatory requirements must be supported by economic viability.

An important contemporary direction is the integration of digital tools into regulatory and economic systems. Reusability analytics tools enable more accurate evaluation of end-of-life scenarios and improve the economic justification for material reuse [24]. However, their application is limited by insufficient data standardization and the need for cross-sector coordination.

Overall, the synthesis of international experience demonstrates that updating the regulatory framework and implementing economic support mechanisms is a critically important fifth principle of the structural–technological transformation of the construction industry. Effective circular systems require mandatory recycling targets, financial incentives for reuse, penalties for landfilling, and the integration of life cycle assessment into public procurement and construction standards.

Based on the conducted assessment of the situation, a SWOT analysis of the implementation of the structural-technological approach was performed (Table.1).

Table. 1. SWOT analysis of the implementation of the structural-technological approach
Табл.1. SWOT-аналіз впровадження структурно-технологічного підходу

S – Strengths	W – Weaknesses
✓ Significant volume of construction waste → creates a strong resource base for reuse ✓ High demand for construction materials in post-reconstruction conditions ✓ Availability of international support and integration with European practices ✓ Gradual implementation of BIM technologies in large-scale projects ✓ Potential for rapid deployment of mobile recycling solutions	✓ Lack of clear standards for the reuse of reinforced concrete ✓ Insufficiently developed recycling infrastructure ✓ Low level of selective deconstruction ✓ Shortage of qualified personnel ✓ Fragmented digitalization (BIM is not used systematically) ✓ Logistical challenges (especially in war-affected regions)

Table. 1. (continued)
Табл.1. (продовження)

O – Opportunities	T – Threats
✓ Harmonization with EU standards → access to funding and technologies ✓ Development of a market for secondary construction materials ✓ Reduction of construction costs through reuse ✓ Development of new industries (recycling, digital platforms, material banks) ✓ Integration of LCA and digital material passports ✓ Acceleration of reconstruction through the use of local resources	✓ High initial investment costs ✓ Economic and security instability ✓ Competition with low-cost primary materials ✓ Risk of formal implementation without real quality ✓ Low institutional capacity in regions ✓ Lack of long-term political consistency

The SWOT analysis shows that Ukraine has a unique combination of factors: on the one hand, critical weaknesses (infrastructure and regulatory framework), and on the other hand, unprecedented opportunities arising from the масштаб of reconstruction. Rapid success with low implementation complexity and high benefit can be achieved in the areas of construction waste sorting and BIM-based regulation. Moreover, progress in these fields is already underway, meaning that digitalization and sorting can deliver quick and tangible results. In contrast, infrastructure development and regulatory policy are decisive for long-term success.

CONCLUSIONS AND RECOMMENDATIONS

For Ukraine, the creation of an effective system for sorting and classification of construction waste is of critical importance in the context of post-war recovery. The absence of systematic sorting leads to the mixing of materials, loss of elements suitable for reuse, and an increase in the volume of waste sent to landfill. At the same time, the implementation of modern European approaches, supported by recent studies from 2024-2026, will not only minimize environmental risks but also create a resource base for reconstruction based on circular economy principles.

The implementation of selective deconstruction is critically important for a country affected by war, as it allows transforming construction debris into a resource base for rebuilding. The integration of this approach with digital technologies, such as BIM, and with Design for Deconstruction principles creates the foundation for a closed-loop system of reinforced concrete use in the future construction sector.

The development of construction waste recycling infrastructure under conditions of large-scale destruction is an extremely complex task. However, without a well-developed network of recycling facilities, it is impossible to effectively utilize the millions of tons of reinforced concrete debris generated. The integration of EU and Asian experience, along with modern LCA approaches, will provide a basis for establishing a national recycling system oriented toward large-scale material flows.

The integration of digital technologies ensures connectivity between design, construction, deconstruction, and recycling processes. The use of BIM and digital material passports creates a unified information system for managing the life cycle of structures, ensuring traceability and improving decision-making regarding reuse and recycling.

International experience demonstrates that digitalization is a fundamental prerequisite for circular construction, as it enables the integration of technical, environmental, and economic parameters into a single system. For Ukraine, the implementation of digital technologies will make it possible to transform construction waste into a manageable resource for reconstruction.

The first step should be the introduction of national BIM standards and the creation of a state system of digital material passports to account for structures and their reuse potential, followed by the mandatory application of BIM in infrastructure recovery projects with automated assessment of deconstruction scenarios. At the same time, it is necessary to train qualified construction professionals capable of working in a digital environment.

Currently, the lack of effective regulatory frameworks and economic incentives limits the large-scale reuse of reinforced concrete waste.

In terms of regulatory changes, the primary focus should be on the development and implementation of permitting documents defining the scope of application of secondary materials, particularly recycled reinforced concrete used as aggregate, as well as structures made from recycled raw materials, including their load-bearing capacity, service life, maintainability, and related characteristics.

At present, urban planning regulations specify only the requirements for the certification of building structures and materials for tender procurement, which may include, among other aspects, the proportion of recycled resources used. At the same time, "green" certification in the EU is becoming an everyday reality.

However, alignment with European approaches, along with the implementation of economically grounded life cycle assessment tools, can create a functional market for secondary construction materials. This will not only reduce reconstruction costs but also transform construction waste into a strategic resource for national recovery, ensuring the transition from a linear to a circular construction model.

ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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КОНСТРУКЦІЙНО-ТЕХНОЛОГІЧНІ ПІДХОДИ ДО ПЕРЕРОБКИ ЗАЛІЗОБЕТОНУ: ІНТЕГРАЦІЯ ТЕХНОЛОГІЙ ПРОЄКТУВАННЯ, ДЕКОНСТРУКЦІЇ ТА ПОВТОРНОГО ВИКОРИСТАННЯ

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Анотація. Перехід від лінійної до циркулярної економіки став визначальною парадигмою сучасної будівельної галузі, особливо в контексті використання залізобетону як одного з найпоширеніших конструкційних матеріалів у світі. У даному дослідженні розглядаються структурно-технологічні підходи до переробки залізобетону на основі інтеграції процесів проєктування, демонтажу та повторного використання. Будівельна галузь є одним із основних споживачів природних ресурсів і водночас значним джерелом утворення відходів, що обумовлює необхідність розробки комплексних стратегій замикання матеріальних потоків і зменшення екологічного навантаження.

Актуальність дослідження є особливо високою для України, де внаслідок воєнних руйнувань накопичено мільйони тонн будівельних відходів. Залізобетонний лом у цьому контексті виступає не лише як екологічна проблема, але і як важливий вторинний ресурс для післявоєнної відбудови. Ефективні стратегії переробки та повторного використання дозволяють суттєво зменшити потребу у первинних матеріалах, скоротити викиди парникових газів і прискорити відновлення інфраструктури.

Запропонований підхід базується на інтеграції ключових етапів життєвого циклу залізобетонних конструкцій, включаючи проєктування з урахуванням демонтажу, селективний демонтаж, відновлення матеріалів та їх повторне використання. Проєктні рішення, орієнтовані на подальше розбирання, дозволяють зберігати конструктивні елементи та підвищувати їх потенціал повторного застосування. Використання технологій селективного демонтажу, на відміну від традиційного знесення, забезпечує формування більш якісних матеріальних потоків і зменшення втрат ресурсів. Розвиток інфраструктури переробки визначається як критичний фактор, що забезпечує можливість перетворення бетонного лому у високоякісні вторинні заповнювачі або придатні до повторного використання конструктивні елементи.

Ключову роль у запропонованій системі відіграють цифрові технології, які поєднують усі етапи життєвого циклу матеріалів. Інформаційне моделювання будівель та цифрові паспорти матеріалів забезпечують простежуваність конструкцій, підвищують обґрунтованість управлінських рішень і дозволяють оцінювати екологічну та економічну ефективність. Ці інструменти формують єдине інформаційне середовище, що підвищує ефективність процесів переробки та повторного використання.

Окрему увагу приділено ролі нормативно-правових та економічних механізмів як необхідної умови реалізації циркулярних підходів. За відсутності відповідного правового регулювання, фінансових стимулів і ринкових механізмів навіть найсучасніші технологічні рішення не можуть бути ефективно впроваджені у широкому масштабі.

Отримані результати свідчать, що інтеграція процесів проєктування, демонтажу та повторного використання в межах структурно-технологічного підходу створює ефективну основу для переходу до циркулярного будівництва. Для України цей підхід є не лише відповіддю на глобальні виклики сталого розвитку, але й практичним інструментом трансформації будівельних відходів у стратегічний ресурс післявоєнної відбудови.

Ключові слова: сталий розвиток у будівництві; BIM-технології; будівництво та демонтаж; повторне використання залізобетонних елементів; оцінка життєвого циклу (LCA)
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