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Focus on Ukraine

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A dual circular strategies hierarchy as a guiding framework for post-disaster recovery and reconstruction: Focus on Ukraine

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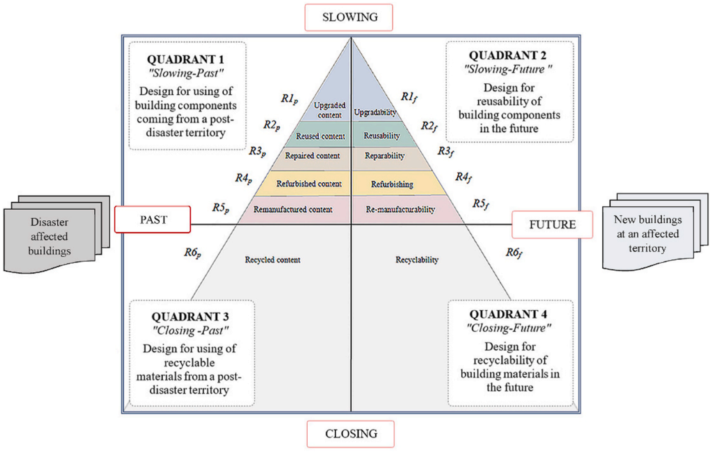
HIGHLIGHTS

- The field of circular recovery and reconstruction is still emerging.
- A dual-hierarchy framework has been proposed to guide circular recovery.
- A typology of design strategies for circular recovery has been introduced.
- Methodological recommendations for assessing post-disaster circularity are given.
- The potential for circular recovery in Ukraine has been explored.

GRAPHICAL ABSTRACT



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ABSTRACT

The circular economy has long been regarded as a key strategy for achieving sustainable development and has more recently been recognized as an effective approach to crisis response. This study contributes to this nascent literature by introducing a dual hierarchy of 6Rs strategies as a guiding framework for circular post-disaster recovery to support the integration of circularity into the United Nations' "Build Back Better" approach. The novelty of the proposed hierarchy lies in the two-vector operationalization of each strategy, considering both past and future perspectives. This dual focus facilitates the recovery of materials and components from disaster-affected buildings, the restoration of damaged structures, and the design of new buildings with a stronger emphasis on circularity. Based on the hierarchy, a typology of design strategies for circular recovery and

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reconstruction has been proposed, structured around four key features, offering practical guidance on how different aspects of circularity can be operationalized in rebuilding efforts. In addition, the study outlines methodological recommendations for assessing the circularity potential of damaged structures, a critical step in planning adaptive and resource-efficient rebuilding. The article also examines the case of war-torn Ukraine as one of the most devastating man-made disasters today. The potential for Ukraine's circular recovery within the framework of global and European Union disaster management mechanisms, as well as the European Commission's policies in the construction industry, has been explored. The study employs a three-step multi-method approach that includes a literature review, critical analysis, and conceptual modeling. Key findings, comprising a dual hierarchy of strategies, a typology of design approaches, and recommendations for circularity assessment, contribute to advancing circular recovery and reconstruction after disasters in various contexts, including war-torn Ukraine, and reflect their practical significance for circular recovery initiatives.

1. Introduction

The consequences of both natural and man-made disasters include significant casualties and the destruction of vital infrastructure. In the aftermath, rebuilding efforts must balance urgency with long-term resilience to ensure sustainable recovery. Post-disaster recovery is a complex process that requires the development of a reconstruction plan informed by the nature of the disaster, the scale of the affected area, and the extent of damage to the built environment. Integrating circular economy (CE) principles and low-carbon initiatives into reconstruction planning can enhance sustainability, particularly in terms of both circular building design (Pomponi and Moncaster, 2017) and construction waste management (Ruiz et al., 2020).

The CE seeks to establish a regenerative economic system to replace the dominant linear "take-make-use-dispose" model by enabling continuous flows of resources throughout the supply chains (Bakker et al., 2014). In the built environment, circular resource flows can be created following four core principles (Bocken et al., 2016): (i) narrowing the loops, which reduces resource consumption through design optimization and dematerialization; (ii) slowing the loops, which extends the lifespan of buildings and products in use through maintenance, repair, and reuse; (iii) closing the loops, which recovers value from products that have reached the end of their functional life through recycling; and (iv) regenerating the loops, which creates environmental and social benefits by enhancing biodiversity, promoting the use of renewable resources, and encouraging community involvement.

In the context of circular strategies or Re-X strategies for the construction industry, recent influential contributions include Eberhardt et al. (2022) proposing a taxonomy of strategies for new buildings, Sharma et al. (2022) identifying 33 global strategies for demolition waste management, and Esa et al. (2017) outlining strategies for construction and demolition waste management. However, existing circular design approaches in construction are generally tailored to stable, non-crisis contexts and often lack the operational specificity required for application in disaster-affected areas with highly particular constraints. Addressing urgent recovery needs, resource scarcity, and the challenges posed by damaged or destroyed buildings requires a more context-sensitive understanding of applicable strategies. This is especially critical in conditions such as Ukraine, where post-conflict recovery involves simultaneously addressing the problem of vast volumes of construction and demolition waste and the urgent need for large-scale housing construction.

Recent contributions to the field of disaster recovery, with an emphasis on CE aspects, have examined case studies from various disaster-affected regions, including post-earthquake Turkey and Syria (Çetin and Kirchherr, 2025; Xiao et al., 2023), Nepal (Khanal et al., 2021), China (Wei, 2023), Ecuador (Criollo and Tapia, 2020), Iran (Askarizadeh et al., 2016), post-tsunami Japan (Ide, 2015), post-flood Italy (Gabrielli et al., 2018), post-war Ukraine (Shevchenko et al., 2024c), post-conflict Gaza Strip (AbuHamed et al., 2023), Libya (Ali and Ezeah, 2017). From a CE perspective, these studies predominantly focus on the recycling and recovery practices of post-disaster waste. Although some studies provide valuable conceptual and methodological approaches to post-disaster waste management, these contributions offer limited engagement with the CE in terms of strategy hierarchies and the integration of circular construction design into rebuilding efforts. Notable exceptions include recent contributions by Çetin and Kirchherr (2025), who integrate four core CE strategies – narrowing, slowing, closing, and regenerating resource loops – into post-disaster recovery and reconstruction, and Hartley et al. (2024), who conceptualize CE as a crisis response mechanism. While the majority of these contributions have advanced knowledge in post-disaster waste management, they primarily assess material recovery rather than holistic strategies for extending the lifecycle of buildings or integrating circular design principles into reconstruction planning. This highlights a significant gap in the application of CE principles to post-disaster reconstruction – particularly in the design of new buildings and infrastructure, as well as long-term management of disaster waste. Moreover, despite its urgency and relevance, Ukraine's recovery remains largely unexamined through a CE lens. Beyond Ukraine, post-war or post-conflict reconstruction in general has received little attention in CE research, leaving a gap in understanding how CE principles can be adapted to address the complex challenges of rebuilding war-torn regions.

To this end, this study aims to develop a framework for guiding circular post-disaster recovery and reconstruction, facilitating the "Build Back Better" approach of the United Nations (Build Back Better in recoveryrehabilitation and reconstruction, 2017) through circular initiatives towards a carbon-neutral Europe, thereby contributing to Ukraine's recovery. In this context, the study addresses the following research questions:

> RQ1: To what extent do existing academic studies examine the application of CE practices in post-disaster reconstruction, and what are their key findings that can further be integrated into Ukraine's recovery?
> RQ2: How can Ukraine's circular recovery be facilitated within the framework of global and EU post-disaster initiatives and European construction policies?
> RQ3: How can circular and climate-neutral post-disaster recovery and reconstruction be enhanced and facilitated, both in general and in the specific context of post-war Ukraine?

The paper is structured as follows. Section 2 outlines the study design, detailing the three-step research process and the findings obtained. Section 3 presents the results of a literature review based on content analysis and summarizes the key insights derived from the review. Section 4 explores the potential of circular and climate-neutral reconstruction of Ukraine after war. Section 5 proposes the dual hierarchy of circular strategies as a guiding framework for circular post-disaster reconstruction, presents the typology of design strategies, and introduces the "circularity potential of a post-disaster" indicator. Section 6 discusses the theoretical and practical implications of the findings. Finally, Section 7 outlines the conclusion of this study.

2. Research methodology

Given the exploratory character of the study, a multi-method approach was employed to address the research questions. This involved a three-step process integrating literature review, critical analysis, and conceptual analysis with theoretical framing. Fig. 1 illustrates the study design, outlining the research methods and resulting key findings. *Step 1* involves analyzing contributions to disaster recovery with an emphasis on CE aspects to identify key areas of exploration, assess the state-of-the-art in the field, and determine the most extensively studied issues. Scopus of Elsevier was selected as the global abstract and citation database for identifying relevant publications. A preliminary search conducted in March 2024 found no contributions specifically addressing circular reconstruction. However, we argue that disaster management as a knowledge domain encompasses aspects related to the circular model, particularly in the context of certain strategies centered on disaster waste management.

To ensure a comprehensive selection of relevant contributions, the following search string was designed to cover key areas of knowledge related to “post-disaster reconstruction” and “disaster waste management”: “disaster” OR “earthquake” OR “tsunami” OR “floods” OR “war” OR “conflict” (search in article title) AND “waste” OR “recycling” OR “debris” OR “destroyed building” (search in article title, abstract, keywords) AND “reconstruction” OR “construction” OR “rebuild” OR “recover” OR “restoration” (search in article title). We limited the first and last keyword combinations (e.g., “disaster”, “earthquake”, “reconstruction”, “rebuild”) to article titles only to enhance the specificity and relevance of the search results. These terms are broad and often appear in various contexts unrelated to post-disaster reconstruction when searched across abstracts and keywords. By narrowing their occurrence to titles, we aimed to reduce the inclusion of unrelated articles and improve the thematic precision of the dataset.

The initial search, conducted on March 24, 2024, yielded 141 documents. The PRISMA flowchart outlining the document selection process is presented in Supplementary Material 1. Given the limited number of studies in this field, the dataset comprised journal articles, conference papers, and book chapters. Furthermore, studies were eligible for inclusion regardless of their publication date or language. The primary inclusion criteria was the relevance of the paper title to the recovery phase of disaster management. To ensure the utmost relevance of the final sample, a mutual screening process was applied, focusing on the abstracts of publications that addressed the operationalization of reuse or recycling strategies. This process resulted in the selection of 25 studies for further consideration (Supplementary Material 2).

Furthermore, this study examines the limited number of recently published works on post-disaster recovery and reconstruction directly related to CE, highlighting that this field is still emerging.

Step 2 examines the potential for circular and climate-neutral reconstruction of Ukraine after the war by analyzing the impact of the war on the built environment, global disaster data in the context of Ukraine, and exploring global and EU disaster management mechanisms. It also investigates the European Commission’s environmental policies within the construction industry. The international and EU regulations of guiding and normative relevance are studied to evaluate the effectiveness of existing response mechanisms and identify potential enablers supporting CE and decarbonization policies. Global natural disaster data on economic damage have been analyzed to identify cases from other countries that could offer useful insights for Ukraine, and to compare these damages with the war-related data from Ukraine.

Step 3 proposes the dual hierarchy of circular strategies as a guiding framework for circular post-disaster recovery and reconstruction, presents a typology of building design strategies, and introduces the “circularity potential of a post-disaster” indicator.

3. Post-disaster reconstruction and circular economy

3.1. Literature review on disaster management with emphasis on the “recovery"

Table 1 summarizes the publications on disaster recovery with an emphasis on CE aspects. The selected articles are categorized into four themes, as presented in Table 1.

The studies grouped under Theme A focus on research challenges and emerging trends in post-disaster recovery and debris management. Afkhamiaghda and Elwakil (2023) conceptualize key constraints in post-disaster construction decision-making. Their review identifies, categorizes, and synthesizes existing literature across multiple domains, highlighting three major areas for multi-criteria decision-making: route planning and infrastructure rehabilitation, site selection for temporary facilities, and prioritization of reconstruction efforts. Yi and Yang (2014) further contribute by mapping research trends in post-disaster reconstruction. They classify these trends according to pressing challenges, such as construction and demolition waste management, stakeholder dynamics, resource allocation, infrastructure restoration, resilience and vulnerability, reconstruction strategies, sustainability, and governance. Zhang et al. (2019) provide a comprehensive review of disaster waste management literature from 2011 to 2019, assessing research across nine thematic dimensions, including planning, waste classification, treatment technologies, environmental impact, economic considerations, and social implications. The study also identifies underexplored areas such as waste separation, quantity estimation, and energy recovery from waste. Finally, Karunasena et al. (2012) examine post-disaster waste management practices and challenges in Sri Lanka. Their findings emphasize that this topic remains relatively overlooked, despite the

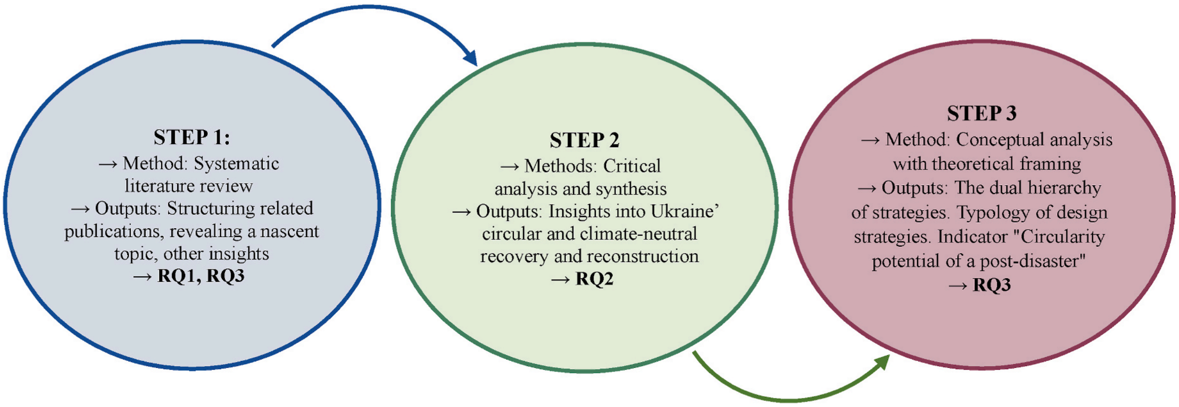


Fig. 1. Study design.

Table 1
Mapping of publications on disaster recovery with a focus on CE aspects.

Source	Type of disaster	Country	Theme	Research focus
Afkhamiaghda and Elwakil (2023)	Disaster	General	A	Challenges in post-disaster reconstruction
Yi and Yang (2014)		General	A	Research trends in post-disaster reconstruction
Zhang et al. (2019)		General	A	Research trends in disaster waste management
Jalloul et al. (2024)		General	B	Critical factors in managing post-disaster materials
Brown and Milke (2016)		General	B	Feasibility factors of disaster waste recycling
Naji et al. (2020)		Iraq	D	Volume estimation of recycled aggregate concrete
Karunasena et al. (2012)		Sri Lanka	A	Strategies and challenges in disaster waste management
Karunasena and Amaratunga (2016)		Sri Lanka	B	Capacity building gaps in managing disaster waste
Kaptan et al. (2024)	Earthquake	General	D	Post-earthquake waste estimation
Domingo and Luo (2017)		New Zealand	B	Limitations in the C&D waste management
Criollo and Tapia (2020)		Ecuador	D	Flows of matter and energy analysis for CE
Khanal et al. (2021)		Nepal	D	Debris volume estimation
Xiao et al. (2023)		Turkey	D	Amount of waste and component proportions
Wei (2023)		China	C	Environment and climate-friendly rebuilding
Zhong et al. (2024)		China	B	Fifteen influencing factors, relationship between factors
Tang and Xu (2013)		China	C	Guidance documents for waste building recycling
Askarizadeh et al. (2016)		Iran	D	Post-earthquake debris volume estimation
Saleh et al. (2023)	Conflict	Palestine	B	Factors of resource availability for reconstruction
AbuHamed et al., 2023		Palestine	C	Disaster waste sorting for reuse and recycling
Ali and Ezeah (2017)		Libya	C	Framework for management of post-conflict waste
Ide (2015)	Tsunami	Japan	C	Disaster waste for embankment and backfilling
Asari et al. (2013)		Japan	C	Strategy for separation and treatment of disaster waste
Seneviratne (2011)		Sri Lanka	B	Failures in disaster waste recycling during reconstruction
Oh and Kang (2013)	Floods	South Korea	C	Guidelines for waste management
Gabrielli et al. (2018)		Italy	D	Quantity and types of post-flood waste generated

A, B, C, D – themes in the field.

scale and hazardous nature of disaster waste. Key challenges include the absence of a clear management hierarchy, weak regulatory enforcement, limited institutional capacity and funding, and inadequate communication and coordination among stakeholders.

The contributions in Theme B examine factors influencing reconstruction and waste management. Brown and Milke (2016) identify seven disaster-specific variables affecting the feasibility of recycling programs, including debris volume, waste heterogeneity, health and environmental risks, spatial distribution, community priorities, funding availability, and regulatory conditions. Jalloul et al. (2024) highlight the interrelated technical, environmental, social, economic, financial, and regulatory drivers shaping sustainable debris reuse, emphasizing the importance of data-driven analysis for informed decision-making. Drawing on the Canterbury earthquake case in New Zealand, Domingo and Luo (2017) outline challenges in construction and demolition waste management, such as limited infrastructure, legal and organizational barriers, and poor coordination. Their recommendations include pre-disaster planning, stronger legislation, sufficient resources, and centralized oversight. Karunasena and Amaratunga (2016) propose a national framework for capacity building in post-disaster waste management, focusing on infrastructure investment, communication, and institutional collaboration. Saleh et al. (2023), analyzing post-war housing reconstruction in Gaza, group resource-related challenges into three categories: stakeholders, project management, and the operational environment – the latter being most influential. Zhong et al. (2024) explore the interdependence of key factors in resource allocation, identifying owner requirements, contractor performance, planning, and data optimization as high-impact areas. Seneviratne (2011) addresses tsunami-related debris as a major environmental issue, calling for clear guidelines for disaster waste management. Key obstacles include non-compliance with regulations, limited land availability, and insufficient knowledge of innovative waste strategies, particularly for the recycling of concrete, bricks, and blocks.

The articles in Theme C focused on the methodological aspects of reconstruction and waste management. These explore resource-efficient disaster waste management, decarbonization in rebuilding efforts, environmental considerations, and waste treatment strategies through case studies of the earthquake in Japan Ide (2015) and China (Ali and Ezeah, 2017; Tang and Xu, 2013), the conflict in Libya (Wei, 2023) and Gaza Strip AbuHamed et al. (2023), the flood in South Korea (Oh and Kang, 2013), and the tsunami in Japan (Asari et al., 2013). Ali and Ezeah (2017) propose a framework for post-conflict waste management in Libya, while Wei (2023) advocates for climate-friendly rebuilding strategies in post-disaster areas in China. The study by Oh and Kang (2013) outlines environmentally sound guidelines for flood waste management, while Asari et al. (2013) introduce the manual Strategies for Separation and Treatment of Disaster Waste, based on available guidelines for disaster waste management in various countries. AbuHamed et al. (2023) contribute to the field by analyzing practical approaches to post-conflict demolition waste management in the Gaza Strip, demonstrating how disaster waste techniques, such as sorting, crushing, and sieving, can be adapted for conflict settings to enable material recovery. Ide (2015) highlight the role of Japan's construction sector in post-disaster waste treatment, emphasizing how public–private collaboration enabled rapid and effective recycling of tsunami debris for reconstruction.

The studies in Theme D encompass contributions on waste volume estimation, types of waste, and component proportions. These studies enhance understanding of waste volume estimation approaches and the quantification of recyclable materials through case studies of earthquakes in Ecuador, Nepal, Turkey, Iran, and flooding in Italy. Of the seven contributions in this theme, five focus on disaster waste volume estimation, including post-earthquake debris volume estimation in

Nepal (Khanal et al., 2021), post-earthquake waste proportions in Turkey (Xiao et al., 2023), post-earthquake waste estimation (Kaptan et al., 2024), post-earthquake debris volume estimation in Iran (Askarizadeh et al., 2016), and the quantity and types of post-flood waste generated in Italy (Gabrielli et al., 2018). Only two contributions are directly relevant to circular economy strategies, namely the study by Naji et al. (2020), which focuses on the volume estimation of recycled aggregate concrete for post-earthquake reconstruction in Iraq, and the study by Criollo and Tapia (2020), which analyzes material and energy flows for the circular economy in post-earthquake Ecuador.

A content analysis of available contributions on disaster recovery, with an emphasis on CE aspects, reveals that most publications focus on the challenges, trends, and influencing factors. Several studies are dedicated to evaluating the volume of debris and materials available for recycling. While some efforts have been made to conceptualize disaster waste management within a recycling framework, a comprehensive approach to circular reconstruction – integrating the recovery of materials and components from disaster-affected buildings, the restoration of damaged structures, and the design of new buildings with a stronger emphasis on circularity – remains lacking.

3.2. *Circular post-disaster reconstruction: an emerging field?*

Several very recently published papers on post-disaster reconstruction related to the CE indicate that this field is only nascent. The first contribution by Hartley et al. (2024) views the CE as a response to the crisis and attempts to push the discourse in this direction. This study explores how the CE can help address converging global crises by examining its impact on technological innovation, supply chains, public policy, and consumer behavior. It highlights key strategies for integrating circularity into crisis management, emphasizing holistic approaches, global value chain analysis, and the inclusion of trade and geopolitical considerations. A very recent article by Çetin and Kirchherr (2025) integrates all four core CE principles – narrowing, slowing, closing, and regenerating resource loops – into post-disaster recovery and reconstruction. The framework developed in response to the 2023 Kahramanmaraş earthquakes in Türkiye, builds on existing disaster risk management and sustainable recovery frameworks. It proposes ten action strategies, ranging from upcycling and reusing disaster waste to introducing new circular policies and business models (Çetin and Kirchherr, 2025).

Additionally, two conference papers focus on circular reconstruction with a particular emphasis on war-torn Ukraine. The first indicates core elements of circular reconstruction in a post-conflict context, including circular design through both singular and configurational strategies, as well as CE-driven post-conflict waste management for recovery and reconstruction. It defines “circular reconstruction of post-disaster territory” as the recovery of disaster-affected areas through circular construction initiatives that integrate design for circularity via the operationalization of Re-X strategies for both damaged and newly constructed buildings (Shevchenko et al., 2024c). The second paper outlines a framework for a circular and climate-neutral post-disaster recovery strategy, positioning it as an essential component of Ukraine’s post-war reconstruction plan (Shevchenko et al., 2025). These contributions represent early-stage research that lays the groundwork for more comprehensive studies on circular reconstruction in post-conflict contexts.

The emergence of studies on circular post-disaster recovery underscores the emerging nature of the field and the increasing academic focus on integrating CE principles into disaster recovery processes.

Overall, the present study, similar to the contributions discussed, explores disaster-affected areas experiencing large-scale destruction of critical infrastructure due to events such as earthquakes, tsunamis, and storms, as well as post-conflict areas characterized by extensive building damage and destruction. These areas require large-scale, comprehensive waste management to address the vast quantities of debris, while simultaneously necessitating the construction of new buildings to support recovery and reconstruction efforts. Consequently, circular reconstruction should encompass two key focal points: (i) disaster waste management and the restoration of damaged buildings based on the operationalization of Re-X strategies; and (ii) circular construction design for new buildings to increase circularity performance in terms of future material recyclability and components reusability. Such designs should also integrate the use of recycled materials and residual building components derived from disaster waste management. When assessing the potential for reusing building components and recycling construction materials, a set of technical and economic factors specific to the conflict-affected area must be considered.

4. The potential for circular recovery and reconstruction for Ukraine

4.1. *Ukraine at war: an overview*

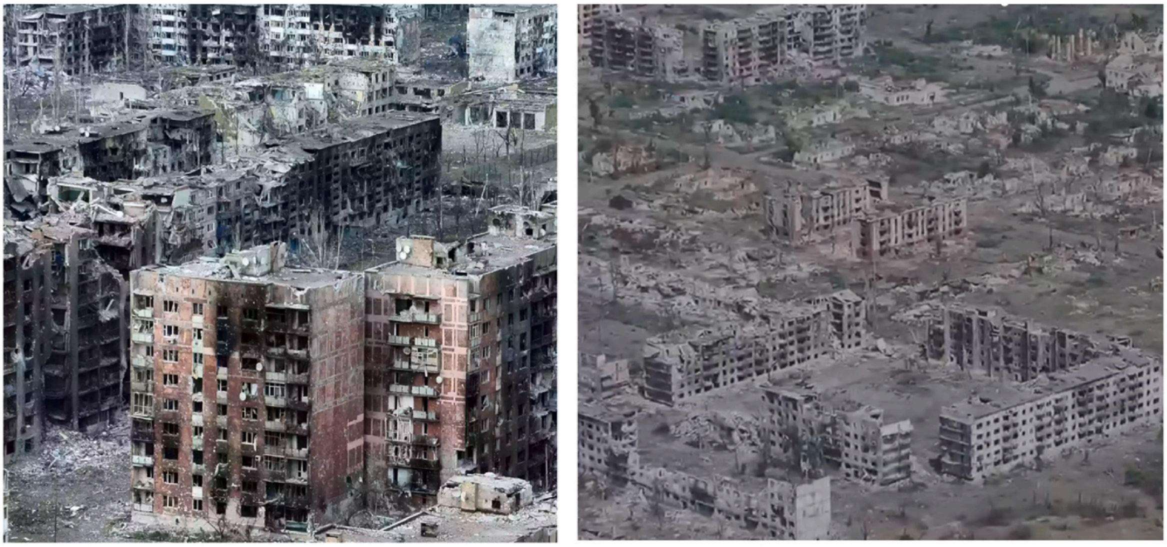
4.1.1. *The impact of war on the built environment*

The Russian invasion of Ukraine has led to the widespread destruction of vital infrastructure across all regions, with the most severe damage concentrated in border areas and occupied territories (Supplementary Material 3). To date, hundreds of towns across Ukraine have been targeted by missile strikes, resulting in severe devastation. Some towns have been completely destroyed, making their post-war conditions comparable to those of post-earthquake, post-hurricane, and post-tsunami regions. Examples of such extensive destruction can be observed in Bakhmut and Chasiv Yar in the Donetsk region (Fig. 2). At the beginning of 2024, the total direct damage to infrastructure from destruction caused by Russia’s military aggression was estimated at 157.2 billion US dollars, according to the Report on (2024) prepared by the Kyiv School of Economics in cooperation with the Government of Ukraine. Data from this report is part of the third Rapid Damage and Needs Assessment for Ukraine (RDNA3) (World Bank, 2023), covering almost two years of the war. The assessment was conducted in collaboration with the World Bank, the European Commission, the United Nations, and the Ukrainian Government. Considering the economic damage structure, the largest shares (% of total sum) fell on residential buildings 37.5 %, infrastructure 23.4 %, industrial assets 8.3 %, agro-industrial complex and land resources 6.5 %, and energy 5.7 %.

Fig. 3 illustrates the distribution of total direct damage across the regions of Ukraine as of early 2024. This map was built based on the data retrieved from the referenced report. As shown in Fig. 3, the highest economic damage was caused to the Donetsk and Kharkiv regions, amounting to 37.374 and 30.224 billion US dollars, respectively. They are followed by the Luhansk, Zaporizhzhia, and Kherson regions, where the damage has reached 17.127, 14.773, and 12.277 billion US dollars, respectively. In terms of the number of affected buildings, the most severe destruction is observed in the Donetsk region, with nearly 91.64 thousand buildings affected, followed by the Kharkiv, Kyiv, and Kherson regions, with 28.01, 23.74, and 22.64 thousand buildings affected, respectively (Shevchenko et al., 2025).

To analyze the hierarchical damage to building infrastructure at the national level across various sectors and sub-sectors, we employ the sunburst chart as a visualization tool. Given our focus on the number of buildings destroyed and damaged in the context of exploring the circularity potential in future research, we exclude from this analysissectors such as industrial assets, the agro-industrial complex, land resources, transport infrastructure, communal services, and energy sector. The data, as of early 2024, were obtained from the referenced report (Report on, 2024) and subsequently aggregated into sub-sectors.

Supplementary material 4 presents the sunburst chart depicting the hierarchical damage, consolidated by sub-sectors in physical, percentage, and value terms. The sunburst chart illustrates two hierarchical levels of categories demonstrating the relationship between outer and inner rings. The chart captures six socio-economic sectors: (i) housing



(a) Bakhmut, Donetsk region, May 2023 *Retrieved from New York Times (2023)*

(b) Chasiv Yar, Donetsk region, August 2024 *Retrieved from Ukrinform (2024)*

(c) Bakhmut, Donetsk region, July 2023. *Retrieved from Official Bakhmut (2023)*

Fig. 2. Scale and degree of destruction (New York Times, 2023; Official, 2023; Ukrinform. Chasiv Yar, 2024).

fund, (ii) healthcare sector, (iii) social sector, (iv) education and science sector, (v) culture, sport and tourism sector, and (vi) trade facilities. As shown in Supplementary material 4, a total of 223,148 buildings across these six sectors were affected, including 76,812 buildings that were destroyed and 146,336 that were damaged, resulting in direct damage of 38.64 billion and 35.276 billion US dollars, respectively. In the multi-apartment buildings sub-sector, 19,276 buildings (10.71 %) were damaged, while 6862 buildings (3.81 %) were destroyed. In the individual housing sub-sector, 118,480 (1.29 %) and 68,693 (0.07 %) buildings were damaged and destroyed, respectively. In some sub-sectors, the proportion of affected buildings reaches one-third. For instance, in the healthcare sector, 29.69 % of hospitals were damaged, and 0.78 % destroyed, which amounted to 1.43 and 0.94 billion US dollars.

Overall, an analysis of damage data over approximately two years of war, reveals the catastrophic consequences of Russian military aggression. The destruction has severely impaired the ability of war-torn towns and cities to provide adequate living conditions, as well as essential educational, medical, and other vital social support.

4.1.2. Global disaster data in the context of the war in Ukraine

This sub-section focuses on the analysis of economic damage of natural disasters to (i) identify cases that could provide useful insights for Ukraine, and (ii) compare these damages with those caused by the conflict in Ukraine. Technogenic disasters, including industrial and transportation accidents (e.g., chemical spills, structural collapses, gas leaks, explosions, and fires), are not included, as they typically do not result in large-scale destruction of critical infrastructures – a defining feature of post-conflict areas, which is the primary focus of this study.

Fig. 4 illustrates the seven costliest natural disasters worldwide from 1980 to July 2023, based on data from the German online platform Statista. During this period, the highest economic damage was recorded at 210 billion US dollars due to the Great East Japan Earthquake and the subsequent tsunami in 2011. Also among the seven costliest disasters were the Kobe Earthquake in Japan (1995) and Sichuan Earthquake in China (2008), which caused economic damage of 100 billion and 85 billion US dollars, respectively. The top seven disasters also include four hurricanes: Hurricane Katrina in 2005, Hurricane Ian in 2022, Hurricane Harvey in 2017, Hurricane Sandy in 2012, with economic damage of 125, 100, 85 and 68.5 billion US dollars, respectively.

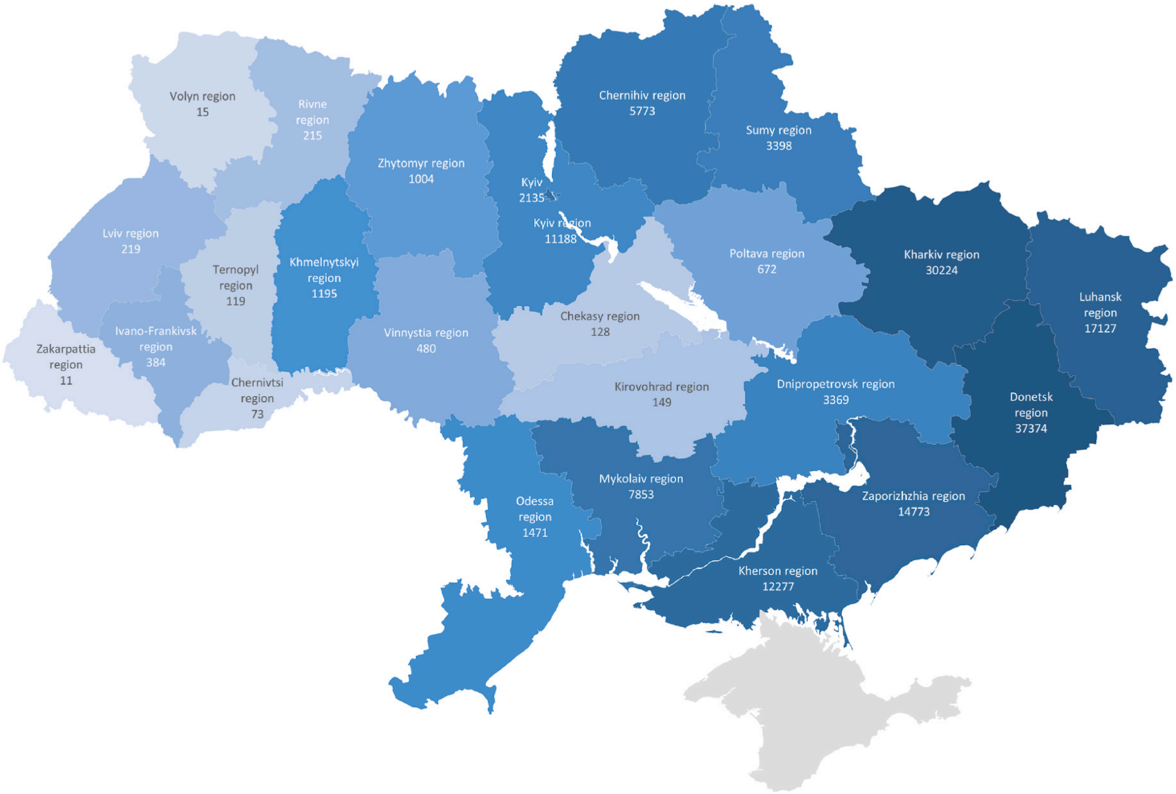


Fig. 3. Total economic damage by regions of Ukraine at the beginning of 2024, million US dollars
Built based on the data of Report (2024).

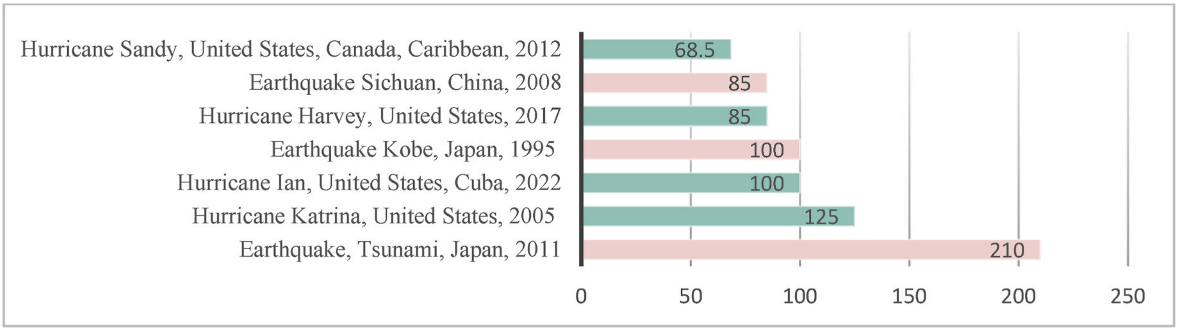


Fig. 4. Top seven natural disasters worldwide by damage cost from 1980 to 2023 (July), billion US dollars
Built based on data from Statista. SocietyNatural disasters (2023).

According to the mapping of earthquake risk worldwide (Li et al., 2021), Asia is the continent with the highest seismic activity and the most earthquakes worldwide. Earthquakes encompass events associated with seismic tremors and tsunamis. The total number of people affected by earthquakes in Asia in 2023 – including those who were injured, required assistance, or lost their homes – is shown in Fig. 5.

Additionally, the figure presents data on the severity and frequency of earthquakes over time in 10 Asian countries, with Turkey and Syria having the highest number of people affected by earthquakes in 2013–9.21 million and 8.81 million, respectively. Furthermore, China recorded the highest number of people affected by the earthquake in 2008 over time, with 47.37 million.

Based on global disaster analyses, it is worth noting that the cases of post-earthquake, post-hurricane, and tsunami-affected countries – particularly Japan (1995, 2011), the United States (2005, 2012, 2017, 2022), China (2008), Canada (2012), and Turkey (2023) – worthy of exploration to advance research in the post-conflict reconstruction field. The experience of these countries could be valuable for conflict-affected regions, including Ukraine, Syria, the Gaza Strip, Sudan, and Abkhazia (Georgia) in implementing "Build Back Better" approach to recovery and reconstruction. In addition, the experience of the mentioned countries merits study in the context of post-conflict waste management, particularly through circular economy initiatives and practices implemented by construction companies. Return to the data on the economic damage caused by Russian aggression to Ukraine to assess the scale of the consequences in comparison with global data. Over the initial three months of the war, the direct damage in Ukraine caused by Russian aggression has reached over 97 billion US dollars (World Bank, 2022a). Then, considering twelve months and almost two years of the war, the direct damages have reached over 135 and almost 152 billion US dollars (World Bank, 2022b, World Bank, 2023), respectively. Given the direct damage growth over two years of the war, it is expected to reach 230 billion US dollars by the end of 2024, and possibly more, given the increased intensity of shelling and extended defense lines. Therefore, it

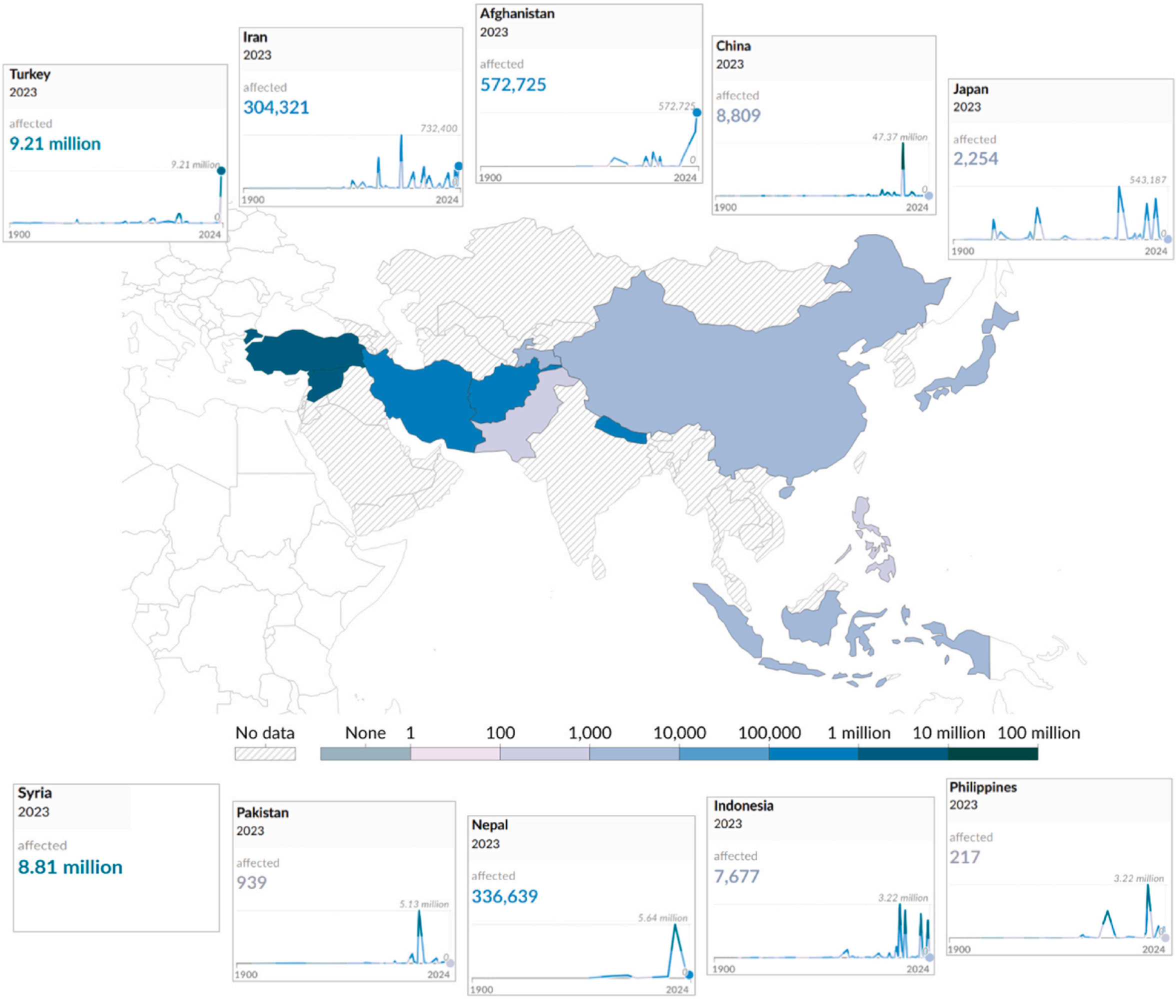


Fig. 5. Total number of people affected by earthquakes in Asia, 2023
Generated and built based on the data Our world (2024).

should be acknowledged that the Russo-Ukrainian war is one of the largest catastrophes in terms of economic damage when compared to global natural disasters from 1980 to 2023, according to the German online data platform "Statista", and may indeed be the largest catastrophe (World Bank, 2023).

4.2. Global and EU disaster management mechanisms

Global initiatives and EU supportive initiatives for Ukraine during war are presented on Fig. 6. The Sendai Framework for Disaster Risk Reduction 2015–2030 is a global United Nations initiative aimed at strengthening national resilience to disasters (Sendai Framework for Disaster Risk Reduction 2015-2030). The framework outlines four priorities for disaster risk management, one of which is "Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction". This priority highlights the need to establish operational mechanisms at both global and regional levels to enhance preparedness and ensure an effective disaster response in situations that exceed national coping capacities.

Since 2008, the United Nations, the European Union, and the World Bank jointly supported post-disaster countries in assessing recovery needs (Adekola O. and Adekola J. 2024) and identifying recovery and reconstruction measures. In this regard, the Joint Declaration on Post-Crisis Assessments and Recovery Planning, European Union, 2008 (Joint Declaration on Post-Crisis Assessments and Recovery Planning, European Union, 2008) was signed by the United Nations, the World Bank, and the European Union. The Declaration is operationalized through the Post Disaster Needs Assessment (PDNA) (PDNA, 2013) for countries affected by disasters, and the Recovery and Peacebuilding Assessment (RPBA) (Joint Recovery and Peacebuilding Assessments) for post-conflict countries. The RPBA is a standardized approach that identifies immediate and medium-term recovery and peacebuilding needs for post-conflict countries. The RPBA report uses standard terminology and incorporates a Building Back Better scheme, principles of green, resilient, inclusive, and sustainable recovery and reconstruction, forming an integral part of the assessment across all sectors (Joint Recovery and Peacebuilding Assessments).

Supplementary Material 5 presents the RPBAs conducted worldwide for post-conflict countries during the period from 2013 to 2021. These assessments include those for Ukraine 2014–2015, Mali 2015, Nigeria 2016, CAR 2016, Cameroon 2017, Burkina Faso 2019–2020, and Mozambique 2020–2021. In addition, RPBA training was for Ethiopia 2018, Thailand 2017, Jordan 2017, and Lebanon 2013–2018, with scoping missions for Libya 2019 and Myanmar 2018 (Foreign Policy, 2024). Furthermore, the review of Experiences with Post-Conflict Needs Assessments 2008–2015 by Donata and Ross (2016) covers the cases of Georgia 2008, Lebanon 2013, Libya 2011, Myanmar 2013, Pakistan 2010, Republic of Yemen 2012. Today, the third Rapid Damage and Needs Assessment for Ukraine (RDNA3) (World bank, 2023) was conducted in collaboration with the World Bank, the European Commission, the United Nations, and the Ukrainian Government. Covering almost two years of the war, the RDNA3 estimates direct damage and losses, as

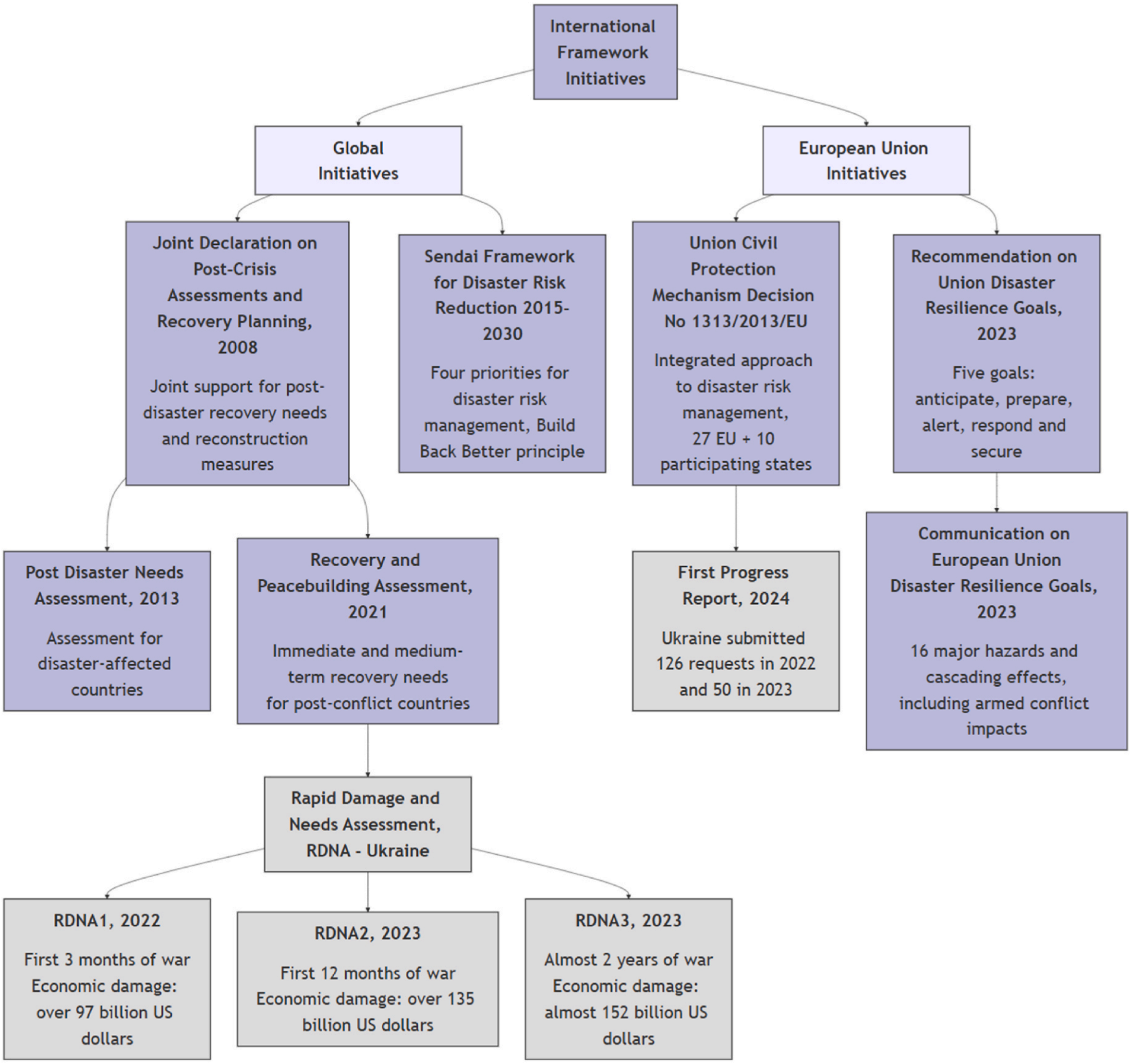


Fig. 6. Global initiatives and EU and supportive initiatives for Ukraine at war.

well as recovery and reconstruction needs for a period of 10 years. RDNA3 builds upon the previous two assessments: RDNA1, which covered the initial 3 months of the war (World Bank, 2022a), and RDNA2, which assessed the first 12 months of the war (World Bank, 2022b). As of December 31, 2023, the recovery and reconstruction needs for Ukraine are estimated at nearly 486 billion US dollars. These needs include both short-term recovery urgent actions and medium-term reconstruction efforts (World Bank, 2023).

The Union Civil Protection Mechanism (UCPM) (Decision No 1313/2013/EU) adopted by the European Union, establishes an integrated approach to disaster risk management to enhance the effectiveness of national systems in prevention, preparedness, and response to all kinds of natural and man-made disasters. When addressing the consequences of terrorist acts and military conflicts, the UCPM can capture only preparedness and response actions. The mechanism consolidates 27 EU member states and 10 other participating states, including Ukraine, which joined in 2023. According to the UCPM Decision, the Commission must "report periodically" every three years on the progress of disaster risk management. The first progress report was issued in March 2024 (Report from the Commission to the European Parliament and the, 2024). Supplementary material 6 presents the number of assistance requests submitted to the UCPM by EU member states and participating states. According to the report, Ukraine submitted 126 requests in 2022 and 50 in 2023. Furthermore, the European Commission recently enacted the Recommendation on Union Disaster Resilience Goals (UDRG) (Commission Recommendation on Union disaster resilience goals, 2023), which establishes five key disaster resilience goals: anticipate, prepare, alert, respond and secure. UDRG are accompanied by horizontal principles, progress reporting, and continuous review and revision to respond to evolving needs and new circumstances. The accompanying document, the Communication on European Union Disaster Resilience Goals: Acting Together to Deal with Future Emergencies (Communication from the Commission to the European parliamentthe council, 2023), elaborates on these evolving challenges, including Russia's aggression against Ukraine. This document identifies 16 major hazards and potential cascading effects to which Europe is exposed, including the impacts of armed conflict. According to Communication, more than half of the EU member states identify earthquakes as one of the primary risks. Overall, the UDRG aim to strengthen the EU's resilience, providing social, economic, and environmental benefits. In terms of environmental benefits, these goals contribute to achieving the objectives of the European Green Deal, particularly in climate adaptation.

4.3. EU policies and Ukraine's recovery

The European Commission's policies in the construction industry are presented on Fig. 7. As shown, the Commissions promotes CE principles in the EU, in accordance with A new Circular Economy Action Plan (European Commission, 2020) and decarbonization strategy aligned with the European Green Deal (Regulation (EU) 2021/1119). According to the Waste Framework Directive 2008/98/EC, 2024, which serves as the legal framework for waste management in the EU, construction and demolition waste is considered a priority waste stream. This Directive establishes the waste management hierarchy in line with the CE-focused strategies outlined in the Action Plan. Supporting documents have been adopted to promote higher-priority Re-X strategies. These include the EU Construction and Demolition Waste Management Protocol (European Commission, 2016), Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings (European Commission, 2018a), and Circular Economy Principles for Building Design (European Commission, 2020a). In addition, the EU Soil Strategy for 2030 has been enacted to regulate the sustainable and circular use of excavated soil from construction and demolition waste (European Commission, 2021).

Furthermore, the European Commission's Communication on the European Green Deal endorses the objective of achieving a climate-neutral EU by 2050, in line with the Paris Agreement's goals. In this context, the EU Policy Roadmap (European Commission, 2018), developed by the World Green Building Council, proposes a new policy plan to accelerate the decarbonization of buildings and construction, one of the most CO2-emitting sectors globally. This roadmap outlines a timeline of recommended actions for EU policymakers to reduce CO2 emissions from building operations, while also addressing the long-overlooked emissions from construction materials, thereby considering the full life-cycle carbon impact of the built environment (European Commission, 2018). To contribute to the European Green Deal and the Digital Decade Policy Programme, the Commission developed the Transition Pathway for Construction (European Commission, 2023). This initiative aims to facilitate a greener construction ecosystem, enable the digital transition as a lever of resilience, and create a favorable environment for competitiveness and resilience.

Overall, the European Commission's environmental policies in construction reflect a strong commitment to advancing CE principles and achieving climate neutrality. The EU has established a comprehensive framework that prioritizes sustainable construction and demolition waste management, promotes circular building design, and supports decarbonization through green building practices and the renewable energy transition. This framework addresses the entire life-cycle carbon impact of the built environment, with digitalization recognized as a key enabler. The norms and standards derived from EU directives, regulations, and guidelines are highly relevant for post-war Ukraine and align with the "Build Back Better" approach, making their incorporation into Ukraine's recovery strategy essential. However, this requires first integrating these documents into Ukrainian legislation.

5. Insights derived from CE literature

Focusing on recent influential studies, several key contributions to the conceptualization and operationalization of CE merit attention. Among the prominent topics in the field, significant works include Bocken et al. (2016), who explore circular business models, Kirchherr et al. (2023) analyzing 221 definitions of CE, Geissdoerfer et al. (2017) investigating CE conceptualization, Bakker et al. (2014) proposing product design strategies, and Saidani et al. (2019) presenting a taxonomy of CE metrics. Notably, recent studies focusing specifically on the circular built environment include Ossio et al. (2023) exploring Re-X strategies operationalization, Pomponi and Moncaster (2017) identifying and framing dimensions of CE, Munaro et al. (2020) offering an overview of the state of the art in CE research, and Hart et al. (2019) identifying barriers and enablers for CE.

These studies, varying in their focus, cover a broad spectrum of Re-X strategies, centering on the closing and slowing of material loops while also considering the broader implications of dematerialization.

W. Stahel was the first to conceptualize the economic system in terms of material loops, distinguishing two primary pathways of circularity: the reuse of products (or parts) and the recycling of materials within technogenic cycles (Stahel, 2010). Stahel posits the axiom of the smallest loop as the most economically viable, emphasizing the importance of product restoration through technical upgrading, repair, modernization, and the reuse of parts and modules in complex products.

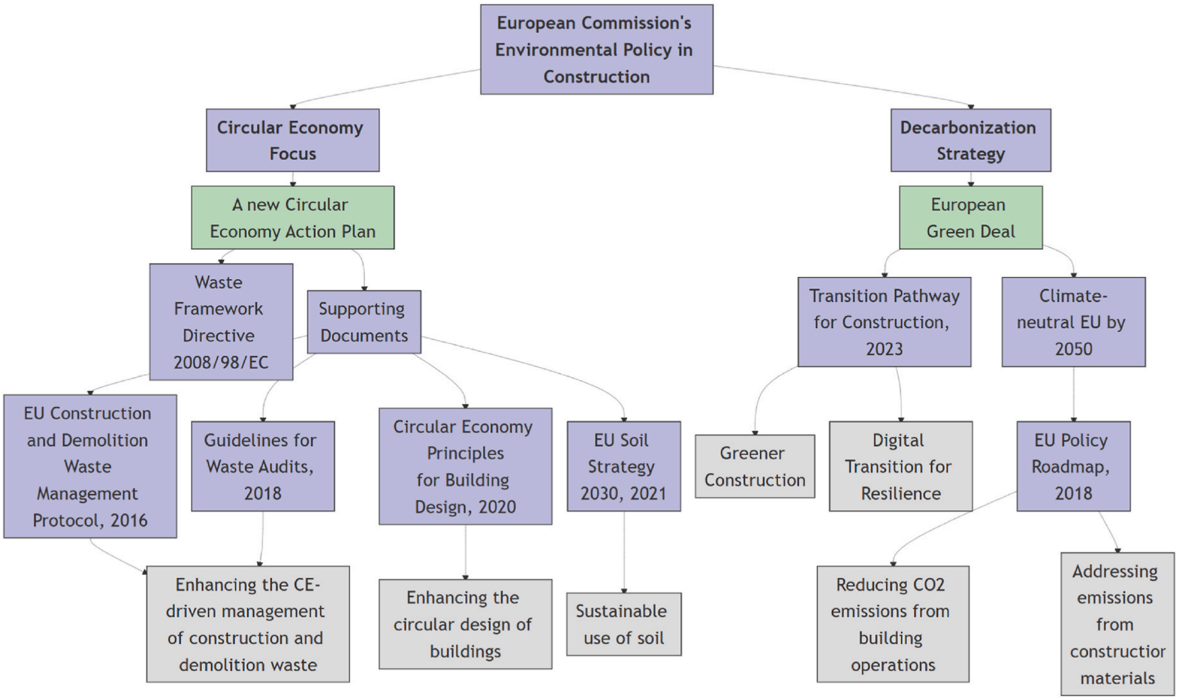


Fig. 7. European Commission's policies in the construction industry.

The principles of closing and slowing material loops have been widely adopted in scholarly discourse, encompassing both product recycling and product life extension through durability, maintenance, upgrading, repair, reuse, remanufacturing, and refurbishing (Den Hollander et al., 2017). Bocken et al. (2016) expand upon the concept of circular inputs within material loops by introducing the idea of narrowing loops, alongside closing and slowing loops, which incorporates dematerialization as a key element of CE theory.

The exact number of Re-X strategies remains a topic of debate, with Modak (2021) supporting the 6Rs framework, while Morseletto (2020) proposes the 10Rs. In the context of circular strategies for the construction industry, recent influential contributions include Eberhardt et al. (2022) proposing a taxonomy of strategies for new buildings, Sharma et al. (2022) identifying 33 global strategies for demolition waste management, and Esa et al. (2017) outlining strategies for construction and demolition waste management. Drawing from these works, the present adopts the 6Rs approach – "upgrading", "reuse", "repair", "refurbishment", "remanufacturing", and "recycling" – as key strategies for closing and slowing material loops, with a particular focus on preserving the value of building components and materials.

These foundational contributions shape the theoretical basis for our conceptual model by framing circularity through the well-established paradigms. Building on this, the present study aligns with the circular design logic developed by Den Hollander et al. (2017) and Bocken et al. (2016), while also integrating principles from disaster recovery frameworks such as the "Build Back Better" approach of the United Nations (Build Back Better in recoveryrehabilitation and reconstruction, 2017). By bringing these two domains into dialogue, we extend the CE discourse to crisis contexts and propose a hybridized framework that anchors circular strategies in the dual focus on recovering value from existing materials and embedding circularity in new construction within post-disaster reconstruction.

This conceptual synthesis is operationalized through the "Closing–Slowing–Future–Past" (CSFP) quadrant model, which we adopt as a practical and adaptable tool for guiding circular interventions in recovery and reconstruction efforts. Overall, the CSFP quadrant includes a range of circularity improvement targets within the framework of slowing and closing material loops, highlighting the dual character of the conventional hierarchy of strategies. While the model does not incorporate "reduce" strategy, representing a limitation, it enables a more nuanced analysis of the dual nature of slowing- and closing-related strategies. Previously, the CSFP model was validated in our studies for simple, complicated, and complex products, including packaging, clothing, electronic equipment (such as a mobile phone), a pump, and a medical device. It serves as a maturity scale for assessing and enhancing circularity performance, incorporating 43 circular design strategies and 225 sub-strategies (Shevchenko et al., 2024a).

In the context of recovery and reconstruction driven by circular initiatives, which are inherently linked to the circular built environment, it is essential to define the primary focal points of these efforts. Disaster-affected areas are characterized by: (i) a specific number of destroyed buildings, which determines the need for new construction; (ii) a volume of construction waste corresponding to the quantity of destroyed buildings; and (iii) a number of damaged buildings requiring repair and restoration. In this respect, circular initiatives should include: (i) designing new buildings with an enhanced emphasis on circularity, (ii) restoring damaged structures, and (iii) maintaining the value of materials and components from disaster-affected buildings. Along these lines, the set of circularity improvement targets for post-disaster recovery and reconstruction must be substantiated.

Regarding the preservation of building materials and components from disaster-affected buildings, it is important to highlight the difference in approaches to managing construction and demolition waste in non-crisis situations (Papastamoulis et al., 2021) and demolition waste resulting from disasters. The challenges of destruction waste management arise from the specific conditions of disaster-affected areas, which often lack essential resources and infrastructure, classifying them as crisis zones (Hartley et al., 2024). Moreover, while construction and demolition waste in non-crisis contexts accumulates gradually over time due to regular activities, destruction waste in disaster scenarios is generated abruptly, necessitating urgent intervention as part of the recovery and reconstruction plan. In large-scale disaster events, such as for war-torn Ukraine, the unprecedented volumes of destruction waste require efficient management strategies to support recovery and reconstruction, including the construction of new buildings, the restoration of damaged structures, and the rehabilitation of other critical infrastructure. In this context, the application of CE principles as a crisis response, as initially proposed by Hartley et al. (2024), is particularly relevant.

Based on the above, it is worth noting that embedding circularity into the "Build Back Better" framework involves a dual focus: using circular strategies for disaster-affected buildings and fostering circularity in future construction. This framework operates along two key vectors: (i) "Build Back Better" by utilizing the circularity potential of destroyed and damaged buildings – minimizing waste through the use of reusable building components and recyclable materials, thus reducing the need for virgin resources; and (ii) "Build Back Better" by ensuring new buildings support long-term circularity – embedding CE principles in the design of new buildings to enhance their adaptability, durability, and recyclability. Together, these two interrelated vectors strengthen the integration of circularity into post-disaster reconstruction, ensuring that rebuilding efforts go beyond mere recovery to create a more resource-efficient and regenerative built environment. To substantiate this claim, we link each vector to specific mechanisms of circularity, namely material recovery from damaged structures and forward-looking circular design in new construction, which directly align with established circular strategies and enable measurable outcomes in terms of resource efficiency and environmental impact. This connection underpins the practical relevance of the approach and supports its effectiveness in enhancing both the credibility and long-term impact of recovery activities.

This analysis leads to the conclusion that integrating the attributes of closing and slowing material loops into post-disaster construction design – both retrospectively and prospectively – maximizes circular impact. Hence, in developing a guiding framework for circular recovery and reconstruction, we propose applying the previously developed "Closing–Slowing–Future–Past" (CSFP) quadrant model (Shevchenko et al., 2022). In our opinion, this model could serve as a reliable tool for providing practical guidance on operationalizing various aspects of circularity in post-disaster rebuilding efforts.

6. Results

6.1. A dual hierarchy of circular strategies for post-disaster areas

Fig. 8 presents the dual hierarchy of 6Rs strategies as a guiding framework for circular recovery and reconstruction of a post-disaster territory (PDT). The extensive destruction and damage to buildings, necessitating large-scale waste management alongside an unprecedented demand for new construction and repair, have led to the development of this hierarchy of circular strategies. Embedded within the "Closing–Slowing–Future–Past" (CSFP) quadrant model (Shevchenko et al., 2022), this hierarchy distinguishes between slowing- and closing-related strategies based on their past- or future-oriented operationalization (see Fig. 8).

The key distinction between the proposed dual hierarchy and the traditional 6R circular strategy hierarchy (Reike et al., 2018) lies in the two-vector operationalization of each strategy, addressing both past and future dimensions to encompass disaster waste management and the design of new buildings.

The upper half of the hierarchy consists of two slowing-oriented targets, incorporating product life extension strategies aimed at saving

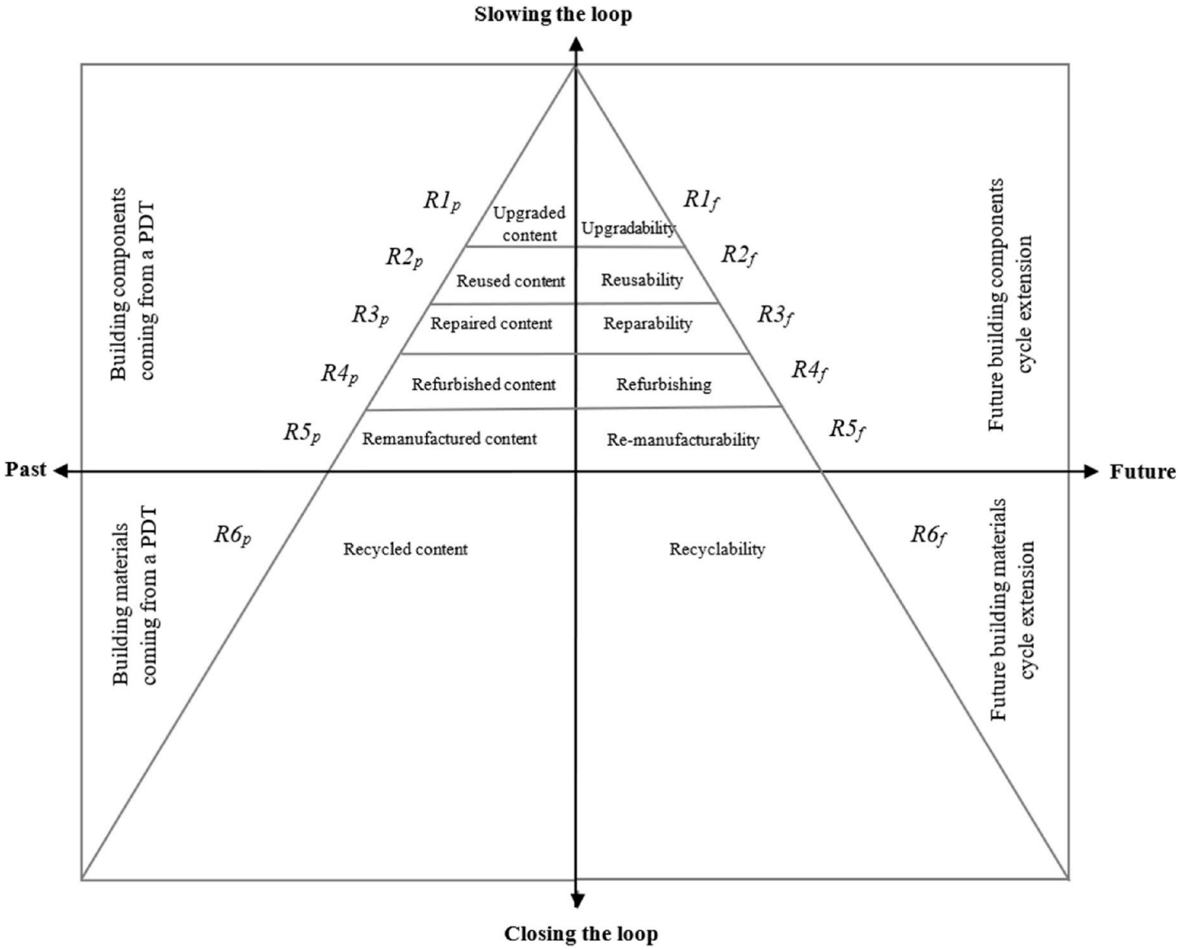


Fig. 8. A dual hierarchy of 6Rs strategies for circular reconstruction of a post-disaster territory.

the value of building components in the present ($R1_p$, $R2_p$, $R3_p$, $R4_p$, and $R5_p$) and in the future ($R1_f$, $R2_f$, $R3_f$, $R4_f$, and $R5_f$). The lower half of the hierarchy, in contrast, comprises two closing-oriented design targets within the ad hoc recycling strategy ($R6_p$, $R6_f$).

6.2. *Twelve Re-X design strategies for circular post-disaster reconstruction*

Fig. 9 presents a schematic representation of circular reconstruction of a PDT based on the "Design for X″ methodology and the dual hierarchy of circular strategies. The scheme identifies four key improvement targets derived from the hierarchy: (i) design for using building components from a PDT, (ii) design for using recyclable materials from a PDT, (iii) design for reusability of building components in the future, (iv) design for recyclability of building materials in the future.

Table 2 presents a description of 12 singular circular design strategies derived from the dual hierarchy. The table indicates the focus area and impact for each strategy presented in terms of "Product–Equipment–Material–Waste" (PEMW) concepts.

Fig. 10 presents a typology of building design strategies for circular reconstruction structured around four features, each reflecting different aspects of circularity and strategies operationalization in the context of the proposed hierarchy.

First, circular design strategies are classified by the type of circularity improvement target based on their temporal orientation and the specific circularity goals they aim to achieve. This dimension differentiates between past- and future-oriented slowing and closing-related strategies, highlighting whether the approach focuses on extending the lifecycle of existing building components and materials or ensuring their reintegration into future cycles.

(a) *Past-oriented slowing strategies* (e.g., "$R1_p$ … $R5_p$") are focused on reducing the consumption of resources by extending the lifespan of existing building structures coming from a disaster-affected area.
(b) *Future-oriented slowing strategies* (e.g., "$R1_f$ … $R5_f$") aim to design and implement new structures with longevity and adaptability, ensuring that future resource use is minimized.
(c) *Past-oriented closing strategies* (e.g., "$R6_p$") involve closing the loop on existing disaster waste streams by recycling materials from previous structures, emphasizing the reuse of waste demolition and other discarded materials to create new building components.
(d) *Future-oriented closing strategies* (e.g., "$R6_f$") are focused on designing new buildings with closed-loop systems, where waste is minimized, and materials are recycled within the construction process, promoting the use of recyclable materials and modular designs that facilitate deconstruction and reuse.

Second, strategies are categorized by the number of strategies operationalized, distinguishing between singular strategies, which operate independently, and configurational strategies, which involve the combination of multiple approaches to enhance circularity performance. This dimension considers the complexity of the approach based on the number of strategies employed.

(a) *Singular strategies* (e.g., "$R1_p$ … $R5_p$", "$R6_p$, $R6_f$") involve the implementation of a single strategy to achieve circularity goals. They are straightforward and focused on specific aspects of resource management.

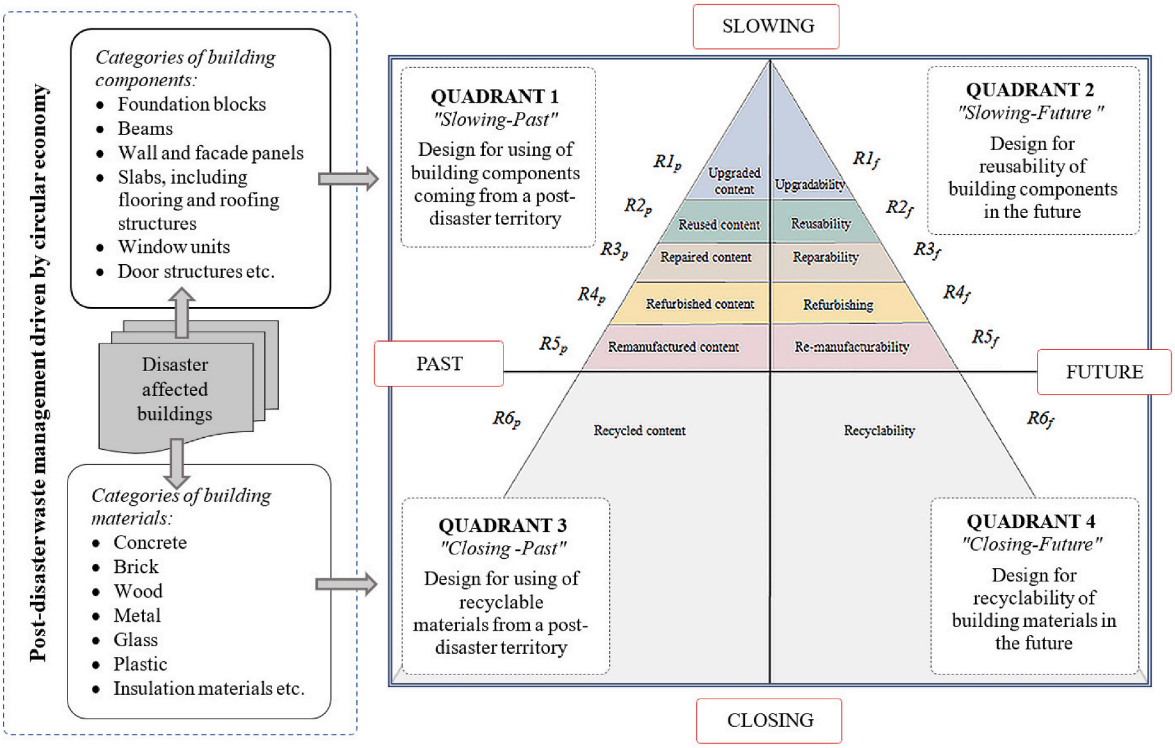


Fig. 9. Four key improvement targets derived from the dual hierarchy for circular post-disaster reconstruction.

(b) *Configurational strategies* (e.g., “$R1_p$ … $R5_p + R1_f$ … $R5_f$”, “$R1_p$ … $R5_p + R6_p$”) combine multiple strategies to achieve a more comprehensive approach to circularity. They leverage the strengths of different strategies to address various aspects of resource use and waste management.

The third feature considers the sequence in which configurational strategies are implemented, recognizing whether strategies are applied sequentially over time or simultaneously in parallel. This dimension examines the temporal sequence in which multiple strategies are implemented:

(a) *Sequential operationalization of strategies* (e.g., “$R1_p$ … $R5_p + R1_f$ … $R5_f$”, “$R6_p + R6f$”) are implemented one after the other, allowing for a phased approach to achieving circularity goals, thereby being beneficial when resources or capabilities are limited.
(b) *Strategies operationalized in parallel* (e.g., “$R1_p$ … $R5_p + R6_p$”, “*R1f … R5f + R6f”)* are implemented simultaneously, enabling enhancing of circular practices. This approach requires robust planning and resource allocation to manage multiple initiatives concurrently.

Finally, the fourth feature evaluates the breadth of improvement targets covered by strategy, ranging from single-target strategies that address one aspect of circularity to more comprehensive approaches that integrate multiple targets.

(a) *Single target coverage strategies* (e.g., *R1p … R5p; R6p*) focus on achieving a single circularity goal, such as reducing resource consumption or closing material loops.
(b) *Two targets coverage strategies* (e.g., “$R1_p$ … $R5_p + R1_f$ … $R5_f$”, “$R6_p + R6_f$”) address two distinct circularity goals, providing a more holistic approach to resource management.
(c) *Three targets coverage strategies* (e.g., “$R1_p$ … $R5_p + R6_p + R1_f$ … $R5_f$”, “*R1p* … $R5_p + R6_f + R6_p$”) encompass three circularity goals.
(d) *Four targets coverage strategies* (e.g., “$R1_p$ … $R5_p + R1_f$ … $R5_f + R6_p + R6_f$”) address four circularity goals, representing the most integrated approach to achieving a CE in post-disaster reconstruction.

Relying on the dual Re-X strategies conceptual model for circular reconstruction, the potential for recycling materials ($R6_p$) and reusing components ($R1_p$-$R5_p$), along with opportunities for their utilization, represents the *circularity potential of disaster-affected buildings*. The development of metrics to assess this potential is crucial for construction companies seeking to implement circular practices (Saidani et al., 2024), as it enables data-based decision-making, facilitates circular investment justification, and enhances the scalability of circular reconstruction efforts.

6.3. Methodological recommendations for evaluating the post-disaster circularity potential

To assess the circularity potential of areas affected by disaster, we propose introducing several new terms into scientific discourse. Drawing on a conceptual analysis of terminology at the intersection of CE and disaster response, a set of terms has been formulated and defined, alongside the development of corresponding evaluative metrics.

Within the framework of the presented dual model, the term *“circularity potential of disaster-affected buildings”* (hereafter referred to as *post-disaster circularity potential*) denotes the estimated quantity of recyclable materials and reusable components available through past-oriented Re-X strategies. These include $R6_p$ strategies aimed at extending material cycles, as well as $R1_p$–$R5_p$ strategies focused on prolonging product life cycles within the scope of circular post-disaster reconstruction. To estimate the quantity of components and materials available for reuse, the assessment should consider the following categories

Table 2
Description of 12 “Re-X″ singular design strategies derived from the dual hierarchy.

	Design strategy	Past-, future-oriented dimension	Focus area based on PEMW categories	Impact	Description
Upgrading	Design for upgraded content – *R1*$_p$	Slowing the loop in terms of the past	Products and equipment coming from disaster-affected buildings	To avoid disaster building waste today	Adding value or improving the aesthetic or functional features of a product, equipment thereby extending the existing cycle of use
	Design for upgradability – *R1*$_f$	Slowing the loop in terms of the future	Products and equipment	Future slowing-related circularity potential	
Reuse	Design for reused content – *R2*$_p$	Slowing the loop in terms of the past	Building components, products and equipment coming from disaster-affected buildings	To avoid disaster building waste today	The reuse of a component, product, and equipment which are still in good condition and performs its original function
	Design for reusability – *R2*$_f$	Slowing the loop in terms of the future	Building components, products and equipment	Future slowing-related circularity potential	
Repair	Design for repaired content – *R3*$_p$	Slowing the loop in terms of the past	Products and equipment coming from disaster-affected buildings	To avoid disaster building waste today	The repair and maintenance of a defective product and equipment to be used with original function
	Design for reparability – *R3*$_f$	Slowing the loop in terms of the future	Products and equipment	Future slowing-related circularity potential	
Refurbishing	Design for refurbished content – *R4*$_p$	Slowing the loop in terms of the past	Building components, products and equipment coming from disaster-affected buildings	To avoid disaster building waste today	The restoring of an old product and bringing it up-to-date state
	Design for refurbish-ability – *R4*$_f$	Slowing the loop in terms of the future	Building components, products and equipment	Future slowing-related circularity potential	
Remanufacturing	Design for remanufactured content – *R5*$_p$	Slowing the loop in terms of the past	Building equipment coming from disaster-affected buildings	To avoid disaster building waste today	The use of discarded equipment’s parts in new equipment with the same function
	Design for remanufacture-ability – *R5*$_f$	Slowing the loop in terms of the future	Building equipment	Future slowing-related circularity potential	
Recycling	Design for recycled content – *R6*$_p$	Closing the loop in terms of the past	Building materials coming from disaster-affected buildings	To avoid disaster building waste today	Obtaining recycled materials of the same or lower quality from the processing of recyclable raw materials
	Design for recyclability – *R6*$_f$	Closing the loop in terms of the future	Building materials	Future closing-related circularity potential	

of disaster-affected buildings, differentiated by the extent of damage and recovery potential: (i) completely destroyed buildings; (ii) damaged buildings that are beyond repair and require demolition; (iii) damaged buildings that are non-repairable but suitable for dismantling. Buildings that can be repaired are excluded from this analysis, as they do not contribute to circularity potential. However, they should be included in the assessment of reconstruction needs.

To ensure that new buildings support long-term circularity, the term *“post-crisis circular built environment”* refers to the circularity of the rebuilt environment achieved through future-oriented Re-X strategies. These include *R6*$_f$ strategies for extending material cycles and *R1*$_f$–*R5*$_f$ strategies aimed at prolonging product life cycles. The overarching goal is to embed future-oriented strategies into design to enhance adaptability, durability, and recyclability.

The term *“circular recovery and reconstruction readiness”* refers to the presence of key prerequisites – such as institutional, infrastructural, and organizational capacity, international support, environmental policies, and a comprehensive strategic framework – necessary for implementing circular recovery as part of a broader reconstruction plan. Such readiness provides the foundation for effectively operationalizing both past- and future-oriented Re-X strategies in disaster-affected areas. It enables the systematic preservation of material and component value within the economic system, reduces resource loss and environmental pollution, and supports resilient, climate-neutral, and future-oriented reconstruction aligned with the “build back better” principle.

To provide a relevant metric, we propose introducing the *“post-disaster circularity potential” indicator* to quantify building components and materials (Shevchenko et al., 2024b) that can be recovered from disaster-affected buildings and used in rebuilding efforts, specifically in the construction of new buildings and the repair of damaged ones.

The assessment should begin with the creation of two key datasets, namely building components by categories and building materials by types.

The *first dataset* pertains to building components, represented by categories $i = \overline{1,n}$ (e.g., foundation blocks, beams, wall and facade panels, slabs, including flooring and roofing structures, window units, door structures for interior and exterior openings, modular fencing elements, cladding panels etc.). These components are associated with various sectors $k = \overline{1,v}$ (e.g., residential, industrial). Assume that a matrix $X = [x_{ik}]$ describes these components’ availability, where each element x_{ik} represents the volume of component i in a sector k. Formally, the size of this matrix consists of n rows representing building components, and v columns representing sectors. Accordingly, its dimensionality is $n \times v$. Thus, the matrix X can be represented as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1v} \\ x_{21} & x_{22} & \cdots & x_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nv} \end{bmatrix},$$

where $i = \overline{1,n}$ – the categories of components of disaster-affected buildings, $k = \overline{1,v}$ – the types of sectors, x_{ik} – the volume of the component i in sector k.

The *second dataset* focuses on building materials, categorized as $j = \overline{1,m}$ (e.g., concrete, brick, wood, metal, glass, plastic, insulation materials, gypsum board, asphalt, ceramics, mosaic and decorative finishes etc.) and grouped according to building types. Similarly, assume that matrix $Y = [y_{jk}]$ describes these materials availability, where each

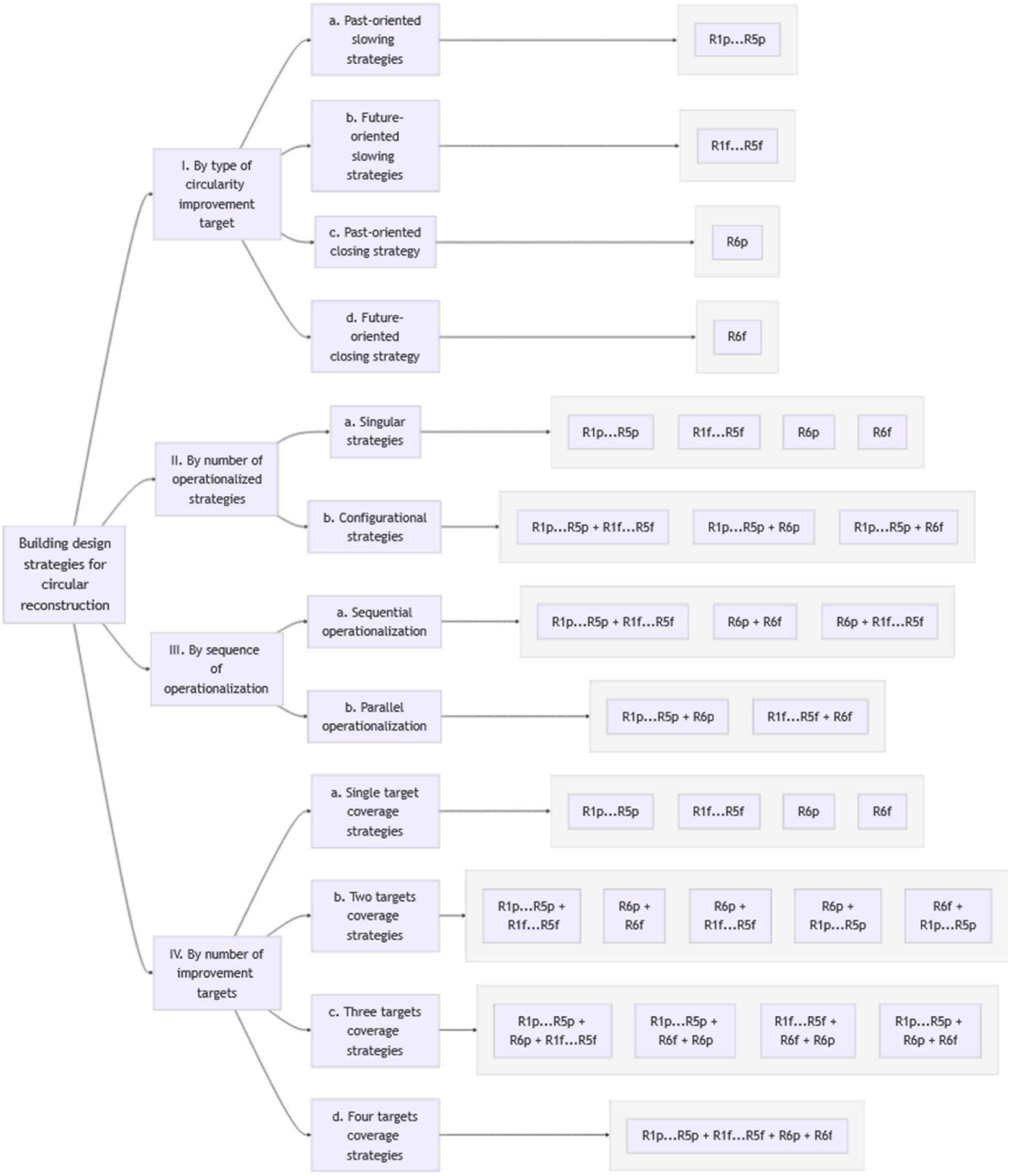


Fig. 10. Typology of building design strategies for circular reconstruction.

element y_{jk} represents the volume of material j in sector k. The size of this matrix consists of m rows representing building materials and v columns representing sectors. Accordingly, its dimensionality is $m \times v$. Thus, matrix Y can be represented:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \dots & y_{1v} \\ y_{21} & y_{22} & \cdots & y_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{nv} \end{bmatrix},$$

where $j = \overline{1,m}$ – the categories of materials, $k = \overline{1,v}$ – the categories of sectors, y_{jk} – the volume of the material j in sector k.

Together, these datasets form the basis for computing reusable components and recyclable materials of affected buildings for post-conflict area reconstruction.

The post-disaster circularity potential (CP_{PDT}), presenting total volume of components available for reuse ($R1_p$-$R5_p$ strategies operationalization) and materials available for recycling ($R6_p$ strategy operationalization), can be expressed as follows:

$$CP_{PDT} = R_{reuse} + R_{recycl} = \sum_{i=1}^{n} \sum_{k=1}^{p} P_{reuse\ ik} + \sum_{j=1}^{m} \sum_{k=1}^{p} P_{recycl\ jk}$$

where R_{reuse}– total volume of components of affected buildings available for reuse, R_{recycl}– total volume of materials of affected buildings available for recycling, $P_{reuse\ ik}$ – the volume of component i of sector k available for slowing the loop ($R1_p$-$R5_p$ strategies operationalization), $P_{recycl\ jk}$– the volume material j of sector k available for closing the loop

($R6_p$ strategy operationalization).

The values of formula terms $P_{reuse\ ik}$ and $P_{recycl\ jk}$ are influenced by various technical and economic factors typical of affected buildings and post-disaster areas. All these factors need to be identified and incorporated into the formula of the post-disaster circularity potential.

To identify these factors, relevant contributions in the field of disaster waste management and construction and demolition waste management were analyzed. Specifically, the analysis focused on the studies by AbuHamed et al. (2023) on disaster waste sorting for reuse and recycling, Brown and Milke (2016) on feasibility factors of disaster waste recycling, Rakhshan et al. (2021) on economic reusability of the building parts, Arora et al. (2020) on reuse potential of building components, Bertino et al. (2021) on buildings deconstruction for reuse (O'Grady et al., 2021), on design for deconstruction.

Relying on these papers, among the technical and economic factors affecting the reuse of post-conflict building components, denoted as T_i and E_i, the following aspects should be considered: damage level of building component ($T_{DL\ i}$), availability of dismantling infrastructure ($T_{DL\ i}$), structural integrity, i.e., component's ability to remain functional after disassembly ($T_{DI\ i}$), dismantling easy without loss of quality ($T_{DE\ i}$), dismantling safety ($T_{DS\ i}$), dismantling costs ($E_{DC\ i}$), and restoration costs ($E_{RC\ i}$).

Similarly, the technical and economic factors influencing the recycling of post-conflict construction materials, denoted as T_j and E_j, should include considerations such as material contamination ($T_{MC\ j}$), recycling infrastructure availability ($T_{RI\ j}$), material separation easy for recycling ($T_{SE\ j}$), safety ($T_{S\ j}$), processing costs ($E_{PC\ j}$), and transport costs ($E_{TC\ j}$).

The integral reusability and recyclability coefficients can be represented as a function of relevant factors, but not limited:

$$\varphi_i = f(T_i,\ E_i) = f(T_{DL\ i}, T_{DI\ i}, T_{SI\ i}, T_{DE\ i}, T_{DS\ i}, E_{DC\ i}, E_{RC\ i}\ldots)$$

$$\sigma_j = f\left(T_j, E_j\right) = f\left(T_{MC\ j}, T_{RI\ j}, T_{SE\ j}, T_{S\ j}, E_{PC\ j},\ E_{TC\ j}\ldots\right)$$

Thus, the total volume of components available for reuse (R_{reuse}) as well as the total volume of materials for recycling $\left(R_{recycl}\right)$ are suggested to determine as follows:

$$R_{reuse} = \sum_{i=1}^{n}\sum_{k=1}^{v} P_{reuse\ ik} = \sum_{i=1}^{n}\sum_{k=1}^{v} x_{\ ik}\cdot\varphi_i$$

$$R_{recycl} = \sum_{j=1}^{m}\sum_{k=1}^{v} P_{recycl\ jk} = \sum_{j=1}^{m}\sum_{k=1}^{v} y_{\ jk}\cdot\sigma_j$$

where φ_i – the integral reusability coefficient for components, σ_j – the integral recyclability coefficient for materials.

Based on the last formulas, the reusable components matrix X' and the recyclable materials matrix Y' can be represented as follows:

$$X' = \begin{bmatrix} x'_{11} & x'_{12} & \cdots & x'_{1v} \\ x'_{21} & x'_{22} & \cdots & x'_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ x'_{n1} & x'_{n2} & \cdots & x'_{nv} \end{bmatrix}, Y' = \begin{bmatrix} y'_{11} & y'_{12} & \cdots & y'_{1v} \\ y'_{21} & y'_{22} & \cdots & y'_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ y'_{n1} & y'_{n2} & \cdots & y'_{nv} \end{bmatrix}$$

$x'_{\ ik}$– element of matrix X', representing the volume of reusable component i of sector k.

$y'_{\ jk}$ – element ofmatrix Y', representing the volume of recyclable material j of sector k.

At this stage, the formula remains hypothetical in terms of its applicability to real-world conditions, as its implementation requires a well-founded justification of coefficient values based on the characteristics of various material and component categories. Moreover, the set of coefficients will inevitably vary depending on the type of disaster, due to differences in the nature of destruction, as well as contextual impact factors. Given these limitations, accurate quantitative calculations are not currently feasible. Instead, we offer methodological recommendations that outline the logic and structure for assessing circularity potential in post-disaster contexts. These recommendations are intended to serve as a foundation for further methodological refinement.

In a forthcoming study, we propose a methodology for assessing the circularity potential of buildings affected by armed conflicts and war. This methodology will be supported by quantitative calculations using data from selected case studies in Ukraine, providing a practical demonstration of the framework's applicability in real post-war reconstruction settings. To determine the volume of reusable components and recyclable materials, this study will apply a set of relevant coefficients derived from factors grouped into five categories: "impact", "perception", "state", "need", and "feasibility". The resulting framework will provide a structured computational approach applicable to post-war or post-conflict reconstruction scenarios.

6.4. *Climate neutrality and circular reconstruction*

Climate neutrality is interconnected with the circular economy. By investing in CE-driven disaster waste management and the construction of new buildings adhering to circular design principles, significant environmental effects can be achieved, particularly in the form of CO_2 emission reductions. These benefits arise from: (i) the prevention of CO_2 emissions during the production of building components from primary materials (since replaced by reused components) and (ii) the prevention of CO2 emissions during the mining and processing of primary building materials (since replaced by recycled materials). Consequently, the application of circular strategies, operationalized through a dual-vector approach in post-disaster areas, enables society to invest in mitigating CO2 emissions both in the present and for the long-term future. Hence, the dual approach of circular strategies operationalization for post-disaster reconstruction leads to a double effect on climate neutrality performance.

If a disaster-affected country has a strong environmental and climate policy, it is particularly well-positioned to invest in circular initiatives as a means of reducing carbon emissions, especially in the construction sector, which is among the largest contributors to global CO2 output. For Ukraine, as a country pursuing European Union integration, this is especially relevant and timely. Given the anticipated scale of post-war recovery and reconstruction, the implementation of CE practices in the construction sector could make a significant contribution to meeting both national and EU-wide emission reduction targets. The proposed dual-vector model further strengthens this potential by simultaneously addressing emissions through the reuse of materials and the integration of forward-looking circular construction strategies, thereby enhancing its overall impact on climate neutrality.

7. Discussion

The findings of this study highlight the emerging and still-developing role of the CE in post-disaster recovery and reconstruction. As a nascent research topic, the implementation of CE principles in disaster recovery remains underexplored, with most existing studies addressing isolated aspects such as material reuse (Naji et al., 2020), waste management (Ali and Ezeah, 2017), or sustainable construction (Jalloul et al., 2024) rather than providing a comprehensive, structured approach.

Building on this emerging discourse, the present study advances the understanding of how CE can contribute to the "Building Back Better" principle in disaster recovery by introducing a dual hierarchy of circular strategies. This hierarchy considers both retrospective (past-focused) and prospective (future-focused) operationalization of CE strategies. As a guiding framework, the proposed hierarchy underscores the importance of integrating CE into disaster response efforts.

While previous studies, such as those by Çetin and Kirchherr (2025) and Hartley et al. (2024), have laid the groundwork by identifying core CE strategies or conceptualizing CE as a response to crises, the present study advances these approaches by structuring them into a dual hierarchy that distinguishes between retrospective and prospective operationalization in post-disaster contexts. This framework builds upon and systematizes earlier contributions by offering a more granular and actionable typology of CE strategies specifically tailored to post-disaster reconstruction, thereby enhancing circularity performance of post-disaster reconstruction efforts. Specifically, it facilitates the preservation of materials and components from damaged buildings, supports the repair of affected structures, and enhances the circularity performance of newly constructed buildings. In addition, the typology of design strategies for circular reconstruction is proposed, offering practical guidance on how different aspects of circularity can be operationalized in reconstruction efforts. These findings contribute to advancing circular and climate-neutral post-disaster recovery and reconstruction efforts, particularly in war-affected Ukraine.

The proposed framework is most effective in contexts where data availability, policy alignment, and institutional capacity allow for the integration of circular strategy into formal recovery and reconstruction planning. However, its application may be limited in settings with weak governance structures, limited technical expertise, or where urgent humanitarian needs override long-term sustainability goals. Despite these constraints, the framework remains transferable to a wide range of disaster types and regional contexts, provided it is adapted to local conditions, resource availability, and regulatory environments.

One of the most compelling applications of the dual circular strategies operationalization approach is in the context of Ukraine's war-torn building infrastructure. The scale of destruction in Ukraine presents an urgent challenge, and circular recovery within the framework of the "Building Back Better" principle is a noteworthy strategy that aligns with Ukraine's ambition to integrate into the EU. Leveraging European Union environmental policies, Ukraine can adopt CE strategies to promote sustainable rebuilding efforts. The integration of CE principles in Ukraine's reconstruction plan aligns with EU goals of climate neutrality and resource efficiency.

A critical role in advancing post-disaster circular reconstruction will play a data platform enabling comprehensive data accessibility and enhancing interconnectivity among stakeholders – actors of circular value chain. In the context of our dual circular strategies operationalization model, such a database should contribute to the two-vector operationalization of strategies, thereby enabling data-driven disaster waste management and fostering circular construction to eliminate building waste in the future. The most relevant data platforms that could serve as the foundation for a database in Ukraine to facilitate circular and climate-neutral reconstruction include the Madaster platform, which enables the creation of material passports (Heisel and Rau-Oberhuber, 2020), and the French National Building Database, which maps the existing building stock (CSTB, 2022). In addition, the German database ÖKOBAUDA offers a standardized database for ecological building evaluations (Dräger et al., 2022), and DECORUM aims to improve resource efficiency in the construction sector (Luciano et al., 2021). Digital technologies could complement these platforms by enabling dynamic data collection and real-time analytics (Çetin et al., 2021), including the Internet of Things and Radio-Frequency Identification (Giovanardi, 2024), Blockchain and Artificial Intelligence (Elghaish et al., 2022), Building Information Models (Charef and Lu, 2021), ICT-based decision support tools (Yu et al., 2022). These technologies also warrant more in-depth consideration for their potential to facilitate post-disaster reconstruction.

As key stakeholders in circular recovery in war-torn Ukraine, construction companies that actively implement circular practices must be prioritized. These practices include circular building design, CE-oriented construction and demolition waste management, and support for climate neutrality initiatives such as green building. Priority should be given to companies with demonstrated expertise in these areas. This is particularly relevant for major players in the construction sector, including manufacturers of building materials and equipment, construction and engineering firms, project design and consulting companies, waste recycling operators, and innovators in sustainable and smart construction technologies.

An analysis of existing disaster management mechanisms indicates that global and EU standardized schemes are generally adequate for addressing contemporary challenges, providing sufficient support for comprehensive post-disaster recovery and reconstruction, including in post-conflict areas. The EU's disaster risk management mechanism aligns with the objectives of the European Green Deal, though primarily in the context of disaster prevention. The Sendai Framework for Disaster Risk Reduction (Kelman, 2015) facilitates the integration of climate neutrality, green building, and sustainable waste management into recovery plans to a certain extent. However, the extent to which post-disaster recovery mechanisms incorporate climate neutrality and CE principles can vary significantly depending on the context, available resources, and regional priorities. When supported by adequate resources, international assistance, and robust institutional frameworks, reconstruction plans can incorporate a diverse set of targets, ensuring a comprehensive recovery while addressing social, economic, and environmental challenges. The European Commission's environmental policies in construction underscore its commitment to CE principles and climate neutrality. The EU's regulatory framework promotes CE-oriented waste management, circular design, decarbonization, and the renewable energy transition, with digitalization as a key enabler. These standards align with Ukraine's "Build Back Circular" strategy and should be integrated into its recovery plan. However, their implementation requires prior incorporation into national legislation.

While the analysis places particular emphasis on Ukraine, the findings are not context-specific and can be applied to other countries affected by conflicts, as well as those impacted by natural disasters. The proposed dual hierarchy of strategies and the typology of design approaches offer a flexible structure that can be adapted to various disaster types and regional conditions. The accompanying methodological recommendations, which define the conceptual and procedural basis for assessing the circularity potential of affected buildings, enable the evaluation of material flows and the identification of pathways for their effective reuse within recovery and reconstruction efforts following disasters such as earthquakes, hurricanes, and tsunamis.

8. Conclusions

To support the "Build Back Better" principle through circular initiatives, this study introduces a dual 6Rs strategies hierarchy as a guiding framework for circular recovery and reconstruction of a post-disaster area. Unlike the traditional 6Rs hierarchy, the dual hierarchy integrates a two-dimensional perspective that considers both past and future operationalization of each strategy. This approach facilitates (i) the preservation of the value of parts and materials from disaster-affected buildings, (ii) the restoration of damaged buildings, and (iii) the future-oriented circular design of new buildings. Additionally, the study proposes a typology of design strategies for circular reconstruction, categorized into four key features that capture various dimensions of circularity and the application of strategies within the proposed hierarchy. Additionally, the article examines the case of Ukraine, currently experiencing one of the most devastating man-made disasters, highlighting the extensive destruction of critical infrastructure and its catastrophic consequences. It also explores Ukraine's potential for circular recovery within the broader context of global and EU disaster management frameworks and construction industry policies. To foster circular and climate-neutral reconstruction in war-torn Ukraine, the findings may serve as a foundation for developing an adequate strategy as an integral component of the country's Reconstruction plan.

This study has several limitations. Firstly, although the algorithm for calculating the circularity potential is presented in a generic form, at the moment, the formula part is hypothetical in terms of real applicability. Currently, it is rather far from practical use, as a range of technological and economic factors must be converted into coefficients with justification of their values, requiring additional data. Future research will focus on refining this computation, developing a methodology for circularity potential assessment in post-conflict areas, with its validation for Ukraine's war-torn areas. Secondly, the dual hierarchy proposed in this paper is limited to the 6Rs strategies for justifying circular reconstruction, rather than covering a broader range of circular strategies. Nevertheless, we recognize the significant potential of this dual approach in operationalizing these six strategies, emphasizing their dual nature and underscoring the importance of considering any product within a regenerative system.

Finally, although this study focuses on a post-conflict Ukraine, its findings are also applicable to regions experiencing large-scale destruction of critical infrastructure due to natural disasters such as earthquakes, hurricanes, and tsunamis.

CRediT authorship contribution statement

Tetiana Shevchenko: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sultan Çetin:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Bernard Yannou:** Visualization, Supervision, Methodology, Conceptualization. **Julian Kirchherr:** Writing – review & editing, Methodology, Conceptualization. **Michael Saidani:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors: Tetiana Shevchenko, Sultan Çetin, Bernard Yannou, Julian Kirchherr, Michael Saidani.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146478.

Data availability

Data will be made available on request.

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Glossary

Circular Economy –: CE
European Union –: EU
Post Disaster Needs Assessment –: PDNA
Recovery and Peacebuilding Assessment –: RPBA
Union Civil Protection Mechanism –: UCPM
Union Disaster Resilience Goals –: UDRG
Post-Disaster Territory –: PDT
“Closing–Slowing–Future–Past” quadrant model –: CSFP quadrant model
Request For Assistance –: RFA
Design strategy for upgraded content –: $R1_p$
Design strategy for upgradability –: $R1_f$
Design strategy for reused content –: $R2_p$
Design strategy for reusability –: $R2_f$
Design strategy for repaired content –: $R3_p$
Design strategy for reparability –: $R3_f$
Design strategy for refurbished content –: $R4_p$
Design strategy for refurbishability –: $R4_f$
Design strategy for remanufactured content –: $R5_p$
Design strategy for remanufacture-ability –: $R5_f$
Design strategy for recycled content –: $R6_p$
Design strategy for recyclability –: $R6_f$