Research paper

Circular Economy for Post-Hazard Infrastructure Restoration: Strategies for Resilience and Resource Efficiency

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Abstract

Climate change, resource depletion, and increasing natural disasters pose significant challenges to society, which combined highlight the need for resource-efficient infrastructure restoration. Whilst circular economy research in the built environment has largely focused on buildings, limited studies address infrastructure assets. Specifically, integrating circular economy principles into post-hazard infrastructure repairs remains unaddressed in existing literature. This research aims to provide relevant definitions and applications of circular R-strategies for infrastructure restoration. A survey distributed to practitioners in Europe and North America reports on the current state of integrating circular practices and perceptions of different R-strategies. Latent Dirichlet allocation and multi-criteria assessment help determine promising strategies, guiding tailored post-hazard recovery interventions. Results demonstrate that Disposal is the most common approach, with Repair and Refurbish strategies currently adopted, and that there is promising interest in Recycle and Reduce strategies for future implementation. This work serves as a reference for academics and practitioners, acknowledging the varying needs of infrastructure resilience planning and promoting both immediate functionality and long-term circularity.

Keywords: Circular Economy · Infrastructure · Repair · Resilience · Sustainability · Post-Hazard Restoration

1. INTRODUCTION

The built environment consumes 50% of raw materials, contributing to 36% of global energy use and 39% of energy-related carbon dioxide-equivalent emissions (Beetz, 2021). Beyond greenhouse gases (GHG), humanity has exceeded six out of nine planetary boundaries, including those for climate change, biodiversity loss, and freshwater use, indicating a substantial risk of sudden or irreversible environmental changes and potential planetary collapse. In response to these challenges, sustainability, circularity, restoration, and regeneration have gained significant attention on the global agenda. Infrastructure is the backbone of a sustainable society, integrated as a system of systems. It includes physical and organisational structures, facilities, equipment, and services essential for societal and economic functioning. Assets like buildings and infrastructure are interconnected through networks, such as municipal pipes forming water systems. The built environment is shaped by networks in transport, drainage, water, energy, and telecommunications, which collectively form systems that are important for maintaining a level of service to society (PAS 2080, 2023).

1.1 Infrastructure Hazards and Recovery

Climate-related disasters have surged in recent decades, resulting in rising expenditure on both preventive measures and post-disaster recovery, with recovery costs alone amounting to $627 billion between 2003 and 2012 (Forzieri et al., 2018; PwC, 2013). The negative effects of natural hazards are exacerbated by climate change, which drives more frequent and severe extreme weather events (Fischer et al., 2021; Frame et al., 2020; Newman & Noy, 2023). Moreover, infrastructure faces compounding risks from multiple or sequential hazards,

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such as recurrent flooding, earthquake-induced tsunamis, landslides, liquefaction, and aftershocks (Akiyama et al., 2020). Post-disaster recovery of infrastructure requires extensive resources, and at the same time, restoring or regenerating the environment implies avoiding further depletion of natural resources. Minimising or eliminating the use of added resources in infrastructure life-cycle management and post-hazard recovery can enable quicker regeneration of the environment and will contribute to bringing the planetary boundaries within safe limits.

The speed of recovery after a hazard event is quantified using restoration functions for infrastructure. Existing models link recovery time to the level of functionality achieved based on damage, such as bridges (Capacci et al., 2022), ports (Verschuur et al., 2020), power systems (Panteli & Mancarella, 2015), water networks (He & Yuan, 2019), and other various assets. The speed of recovery, also referred to as rapidity, is influenced by the extent of the damage, the availability of resources, and the desired level of operability (Mitoulis et al., 2023). Rapidity is modelled through restoration and reinstatement functions, which link recovery time to the restoration of structural capacity and operability respectively (Argyroudis & Mitoulis, 2021). Restoration of structural capacity requires extensive material and energy resources and is of concern to circularity. The restoration process can be broken down into a series of construction tasks that require appropriate resources. The resource amount depends on the level of damage resulting from the hazard. In resilience modelling, this can be obtained through a probabilistic approach and expert judgement, and for post-hazard conditions, this is through site surveys and investigations. Damage levels are typically divided into minor, moderate, extensive, and severe (Mitoulis et al., 2024).

Once damage levels are identified, corresponding mitigation strategies need to be carried out to maintain the performance throughout the service life of a structure. To decide whether a repair should be carried out and what type of repair should be performed, the severity of damage should be evaluated and categorised (Mitoulis et al., 2023). For instance, in a concrete bridge subjected to a flood, minor damage would be associated with the cracking of structural elements or a road surface, whilst a severe damage level would correspond to partial collapse of a structural element. In a synthesis of disaster management planning for resilient roads, researchers conduct a systematic review and semi-structured interviews to propose strategies for resilience steps (Caldera et al., 2021). These include robustness for prevention, redundancy for preparation, resourcefulness for response, and rapidity for recovery (Caldera et al., 2021). Therefore, the ability to rapidly mobilise locally available materials in post-hazard recovery becomes strategically important for infrastructure restoration.

1.2 Defining a Circular Economy

Circular economy (CE) is not a new concept, but it has received significant attention in the past few years, and as a result, the definition is fluid and dependent on the scale and type of application and the industry (Kirchherr et al., 2017; Reike et al., 2018). Kirchherr et al. (2023) gives the following definition after reviewing over 200 proposed definitions, "The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities."

Four key principles—slow, close, narrow, and regenerate— have also been proposed for a circular built environment (De Wolf et al., 2024). These principles emphasise sustainability at multiple levels. *Slow* refers to extending the lifespan of buildings and materials through durable design and maintenance. *Close* focuses on minimising waste by creating closed-loop systems, where materials are reused locally. *Narrow* aims to reduce resource consumption by optimising efficiency in both material use and energy performance. Finally, *Regenerate* emphasises the importance of restoring and enhancing ecosystems through sustainable construction practices, allowing the built environment to contribute positively to natural cycles and society rather than depleting them. Together, these principles offer a framework for resilient, sustainable urban spaces that align with CE goals.

Traditional understanding of sustainability and CE is operationalised through the terms "reduce, reuse, and recycle," but the set of terms has been expanded in practice and research. They are called R-hierarchies, R-imperatives, R-principles, the waste hierarchy, value retention options, or R-strategies; the latter term is used for the duration of this work (Kirchherr et al., 2017; Reike et al., 2018). Previous efforts to harmonise the growing set of R-strategies have been conducted, most notably by Potting et al (2017), Kirchherr et al (2017), and Morseletto (2020) (who included a Rethink strategy), and Reike et al (2018) (who included a Re-mine strategy). Additional research expands the potential strategies to also include “Regenerate” which was defined as not only using fewer resources but also restoring ecosystems (Henry et al., 2020), and was found in about 25% of 221 CE definitions (Kirchherr et al., 2023). While a Regenerate strategy may be considered fully circular, the next set of strategies, Refuse, Rethink, and Reduce, can be categorised as smarter product use and manufacturing. Next, Reuse, Repair, Refurbish, Remanufacture, and Repurpose are categorised as extending the lifespan of products and their parts. Lastly, Recycle, Recovery, and Re-mine are classified as useful applications of materials (Morseletto, 2020). The business-as-usual practices of disposal and landfill are considered linear practices.

1.3 Circularity in Infrastructure

Often, the broader understanding of circular strategies in the construction industry just considers material recycling (Sadiq & Khalfan, 2024), particularly within infrastructure (Santolini et al., 2024). Although this is still an important strategy, there are several other approaches, across material, the component, asset, or network level, that could be considered. One of the most relevant works is from Çetin & Kirchherr, who combine a literature review, workshop, and interviews to develop a Build Back Circular framework (2025). The framework proposes ten action strategies that combine CE and disaster management derived from the context of the 2023 earthquakes in Türkiye, including the implementation of new circular policies and incentives. In the context of managing materials after a disaster, Yeşiller et al. (2023) develop a reconnaissance framework based on a workshop with stakeholders on the methods, challenges, and guidelines for sustainable materials management. MacDonald & Gowler (2023) focus on the development of a reused materials market in the UK as a result of pre-redevelopment and pre-demolition audits for infrastructure projects, which could be adopted for post-hazard applications. Mhatre et al. (2021) reviewed the circularity potential of bitumen, steel, and concrete in Mumbai's land transport infrastructure using an 11 R-strategies framework. Providing field-based insights and policy suggestions for India’s construction industry. Jensen et al. (2020) explored circularity in UK offshore wind farms, considering the specific materials (e.g., rare earth metals and fibre-reinforced polymer). They proposed a waste hierarchy for wind turbines, viewing decommissioning as a point of regeneration.

For circularity at the component and asset level, Teigiserova et al. (2023) analysed product-service systems in the Dutch context of bridge decks, guide rails, road lights, municipal roads, and provincial roads. The results are a proposed three-step framework for circularity in infrastructure, including incorporating the R-strategies, quantifying material circularity, and evaluating both. The potential implementation of each R-strategy for each pilot case was provided, as well as an input-output model of material flows (Teigiserova et al., 2023). Coenen et al. (2020) produced a CE Interface Matrix Analysis framework that aimed to connect bottom-up to top-down approaches in CE for practitioners in infrastructure through two Dutch case studies (a bridge and a distribution transformer). They provided rank-ordered CE actions that broadly include strategies on repairs and reducing materials. Coenen et al. (2021) and Anastasiades et al. (2023) introduced CE frameworks, including various indicators such as design input, resource availability, adaptability, and reusability. The latter framework adopts partial indicators for material scarcity, structural efficiency, and service life.

O’Leary et al. (2024) explored CE implementation strategies, barriers, and enablers in the context of UK rail infrastructure by using an online survey (n=50) and semi-structured interviews. The survey used a four-point Likert scale and included different life-cycle stages, including end-of-life. Some of the results align with existing expectations that the rail industry is more risk-averse, resistant to change, and perceived as a more permanent infrastructure. Their findings reveal the importance of emphasising circularity in early design and project briefing stages. The top three barriers were a short-term cultural vision, a lack of ownership between client and operator, and resistance to change. Existing research also compares decision-making methodologies used for waste management in a CE context, but does not examine specific CE strategies (Palafox-Alcantar et al., 2020). Thus, there is a nascent precedent in circularity research for waste management and infrastructure, but a lack of work examining circularity in a post-hazard context for infrastructure.

1.4 Research Aim

The specific problem faced in practice is how to restore the level of service of an asset while minimising the use of virgin material. Therefore, the aim of this research is to position the R-strategies defined for a CE in the context of infrastructure, further extending their application into the built environment. To focus the scope, the work is narrowed down to a specific post-hazard state where restoration is needed. This precludes the consideration of the R-strategies for new construction or end-of-life scenarios to focus on decisions made during the lifetime of an infrastructure asset. Although the scope is not limited to certain types of infrastructure, nor limited to a specific region. Specifically, the research question asked in this work is how post-hazard infrastructure restoration strategies are currently, or could be, informed by CE principles.

2. METHODS

Granting that the intersection of CE and infrastructure is nascent in literature and thus exploratory, this work adopts a constructivist research methodology. The answer to the research question is a generated interpretation constructed by the combined perspectives of practitioners. This is developed using qualitative methods through surveys built based on the researchers' literature review and analyses. The framework for informing post-hazard infrastructure restoration with circular strategies is synthesised and proposed along with recommendations for future research directions and potential means for further validation and testing.

The first step involved reviewing the literature on post-hazard infrastructure asset restoration strategies, potential precedents on CE for infrastructure construction, and CE strategies more broadly to find potential areas of relevance. From the review, a list of circular R-strategies was aggregated from the literature, constituting twelve previously defined strategies and one business-as-usual. The definitions were tailored by the authors for their context in infrastructure restoration. Next, four levels of applicability were defined according to the literature on damage states for each circular strategy (Anbazhagan et al., 2012; Lethanh et al., 2018; Yoon et al., 2021). Only damage stages 2-4 of what is defined in literature were used in the survey because “No Damage” does not require a restoration strategy, and “Total Loss” requires a complete new build.

- None Apply: Not used or considered.
- Minor Damage: There are slight damages that do not significantly impair functionality.
- Moderate Damage: Involves noticeable damage that affects the functionality of the infrastructure.
- Severe Damage: Heavily damaged and may be partially or completely non-operational.

The next step of the process involved developing and distributing a survey using a similar method adopted by Saidani et al. (2019). The purpose of the survey was multi-faceted. Initial demographic data was collected, including gender, country of work, years of experience, type of infrastructure worked on, and the name of their position. Then, it aimed to capture the current state-of-the-art in practice for any existing implementation of circular strategies in infrastructure restoration. This was done by first asking the respondents how they defined CE in the context of infrastructure and then asking if each pre-defined strategy is currently being used per damage state. The next set of questions aimed to move beyond current practice and understand potential future development and implementation of circular strategies. The survey asked if, ideally, a strategy were to be implemented, then at what damage state would it be. Additionally, the survey asked about the perceived economic value, perceived GHG savings, perceived resource savings, and perceived effort of implementation to understand potential barriers and enablers for future work. The survey ended with open questions on other strategies that should be considered.

The survey was distributed to people in the United States, the United Kingdom, and Europe through a non-probability sampling via direct email. The initial distribution was to practitioners known to the authoring team, infrastructure asset managers of different government regions across the target countries, and managers within international infrastructure firms. Additional distribution was through postings on LinkedIn. Final responses totalled fifteen and were analysed along the dimensions previously described. There were two approaches to the analysis. For the open-ended survey questions, the text was analysed using latent Dirichlet allocation (LDA), a natural language processing technique. The first step was to preprocess the text data, including tokenisation and removal of stop words and special characters. Then the unsupervised machine learning model identified underlying themes within the text and produced a predefined set of topics for interpretation by the authors. In addition, the Likert responses were visualised using a heat map analysis. This was chosen as an approach to view all the data in a compact and comparative manner.

3. RESULTS & INTERPRETATION

This section is broken into the proposed circular intervention strategies, the results from the survey, and a multi-criteria assessment of perceived factors.

3.1 Proposed Circular Intervention Strategies

Literature slightly varies in how it defines the application scale for circularity (Luthin et al., 2024; Saidani et al., 2019). Although the macro level is well understood at the urban level and beyond, the meso level is sometimes defined as an eco-industrial park or the business level. Luthin, et al. (2024) places companies at the micro level, and de Oliveira (2023) places individual businesses at the micro level. Our research focuses on infrastructure assets and their components and materials, so it effectively varies from the meso to nano levels depending on the specific strategy. There are two significant papers in the extant literature defining a set of 10 R-strategies (Potting et al., 2017; Reike et al., 2018). Both sets have nine overlapping strategies and two unique ones. This total set of 11 strategies is complemented by a forward-looking R-strategy, Regenerate, used by Kircherr (2023), Morseletto (2020), and Geissdoerfer (2017). Lastly, Disposal was added to represent the business-as-usual strategy for the baseline, to a total of 13 strategies listed in Table 1 below. The definitions were tailored to infrastructure contexts, and examples were proposed by the authors to illuminate the definition to the survey takers.

Table 1. Aggregated list of R-Strategies with a German Translation, Definition, and Examples

R - Strategy **(German Translation)**	**Proposed Definition**	**Example**
Disposal *(Beseitigung)*	Demolish and send all materials to the landfill or incineration without energy recovery	Business as usual
Re-mine *(Weiterverwertung)*	Extracting useful materials from landfills or other secondary material sources and adopting them in asset restoration	Backfill, concrete, rubble, etc.
Recover *(Energetische Verwertung)*	Use the waste materials for energy recovery	Construction elements or materials coming from biological cycles, such as timber or bamboo, being burned in waste-to-energy plants
Recycle *(Wiederverwertung)*	Recycle elements and extract useful materials for processing into new elements	Recycled concrete aggregates, steel from rebars from a reinforced concrete column
Repurpose *(Weiterverwendung)*	Use a component extracted from an existing structure in a new structure with a new function	Using a deck element as a wall element
Remanufacture *(Wiederaufbereitung)*	Use the remaining parts from reclaimed components or discarded products in a new functionality	Using off-cuts from a beam being used as separate elements
Refurbish *(Erneuern)*	Restore the asset back to its previous functionality by replacing, repairing, or upgrading	Complete resurfacing of an asset
Repair *(Reparatur)*	Repair part of a damaged asset	Repairing potholes, local resurfacing, etc.
Reuse *(Wiederverwendung)*	Reuse elements extracted from existing assets that still fulfil their original function and retain value in the restoration	Reuse of untampered guard rails or crash barriers
Reduce *(Reduzieren)*	Decrease the use of raw materials in the asset restoration	Optimising the utilisation ratio of structural components
Rethink *(Umdenken)*	Reconsider the use of the asset	Increase the post-recovery functionality above the baseline level
Refuse *(Verzichten)*	Refusal to procure virgin materials to restore the asset	The use of materials already in the stock or from bio-based sources that are regenerative by nature

Regenerate *(Regenerieren)*	Adopt strategies that go beyond the physical and material aspects and address issues with a net-positive impact on climate, biodiversity, and the well-being of communities	Increasing biodiversity in the surrounding landscape of the infrastructure

3.2 Survey Results

The survey received fifteen total responses, of which thirteen were male and two were female. 47% of the respondents had 20 years or more of experience in the infrastructure sector. About 60% of the types of assets worked on were transportation, 20% were water assets, 15% were energy assets, and 5% were on materials. Respondents held various roles, including government (30%), asset owners (25%), researchers (15%), contractors (15%), and engineering consultants (15%). Lastly, the respondents reported working on projects across North America and Europe.

After the demographic questions, the first question was about how the respondents would define or imagine a CE in the context of infrastructure. Common themes in the responses included recycling of materials, using the excavated materials, and keeping assets in use for as long as possible. Using the LDA topic modelling, the top three topics on defining CE for infrastructure were: reusing possible existing materials, recycling used and waste materials, and using materials in infrastructure construction for as long as possible.

3.2.1 State-of-the-Art

The next set of questions asked two sub-questions for each R-strategy. The first was what is the highest damage state of an asset to which the circular strategy is currently applied, and the second was what is the highest damage state this strategy should be implemented in the future. The damage states provided were severe, moderate, and minor, and an option for none applies. Figure 1(a) below shows the summed count of the circular strategies per damage state. Many strategies, including Regenerate, Refuse, and Rethink, are seldom considered in current practice. The most applied approach is Repair, followed by Refurbish and Disposal. When comparing these findings to respondents' views on future adoption (Figure 1(b)), there was a notable shift from "none apply" to use at moderate and severe damage levels.

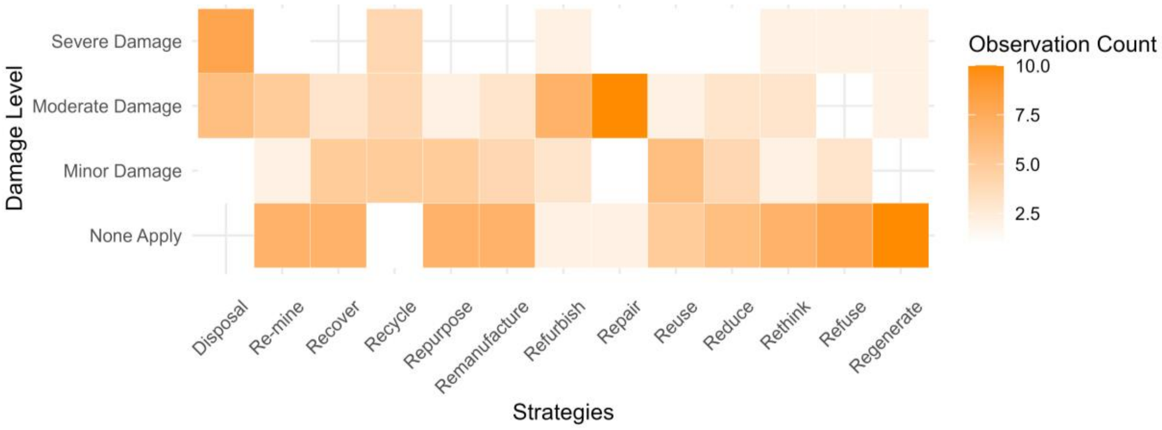

Figure 1(a). Reporting of present use of circular strategies by the maximum applicable damage level

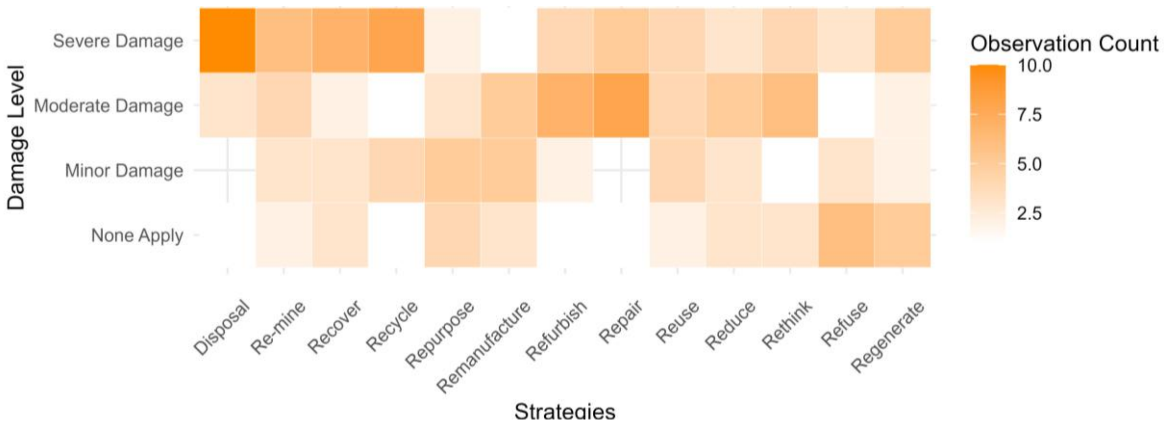

Figure 1(b). Reporting of suggested future use of circular strategies by maximum applicable damage level

Refuse and Regenerate remain relatively frequently reported as having no application in post-hazard recovery. Although no justification was collected in the survey, Refuse might be perceived as having no application because, after infrastructure is damaged or destroyed, some level of service must eventually be restored. Regenerate may also be perceived as not being applicable, as it is the most aspirational state, extending beyond the system boundary of the asset level of service. In all strategies, there is a tendency and interest for increased adoption in the future for higher damage levels (Figure A1). This implies higher relative resource and GHG savings for post-hazard interventions of existing infrastructure. If the infrastructure stock stays the same and practitioners move to adopt the suggested strategies, then there is an implied net benefit.

3.2.2 Stakeholder Perceptions

The next set of questions posed four questions about the respondents' perceptions related to each circular strategy.

- What is your perceived effort to implement this strategy?
- What are your perceived net resource savings from using this strategy?
- What are your perceived net GHG emissions savings from this strategy?
- What is your perceived net economic benefit from using this strategy?

These were rated on a five-point Likert scale from none to very high. The results are shown in Figure 2 below, where the perceived effort is coloured in red to indicate negative implications, and the perceived savings of money, GHG, and resources are coloured in green to indicate positive implications. The results show Disposal and Recover being the lowest effort, but after that, Reduce, Repair, and Rethink as the next lowest effort strategies. Repurpose, Reuse, and Remanufacture are perceived as requiring the highest effort. While Repair and Refurbish are perceived as having the most savings.

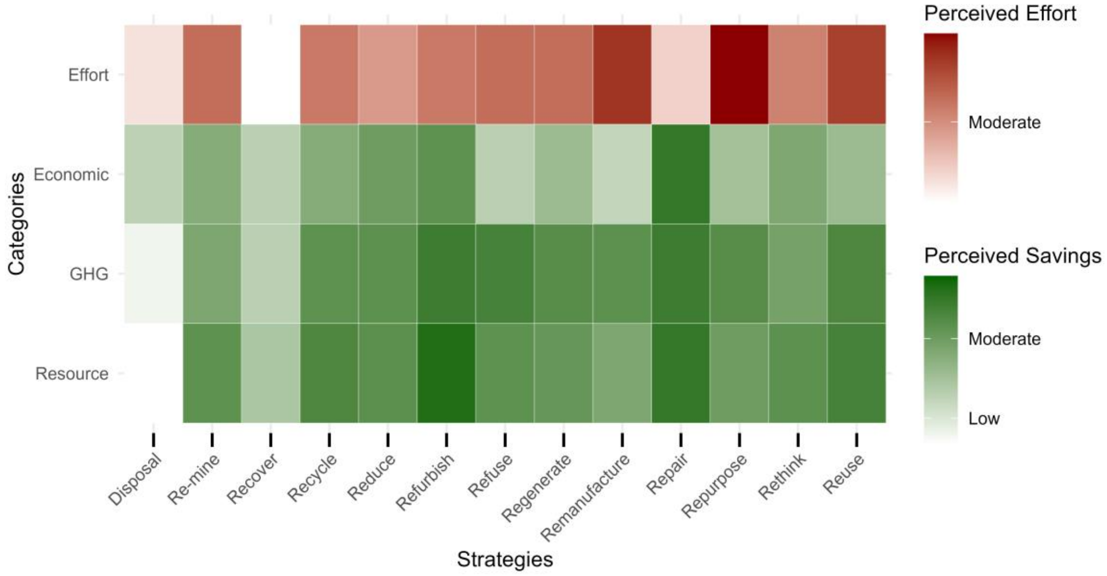

Figure 2. Average perceived effort and savings per circular strategy

3.2.3 Open Comments & Additional Considerations

The last two questions were on general comments and if there are other circularity strategies (either currently or potentially used) to be considered for infrastructure assets. The main theme repeated for additional strategies is to increase the service life and resilience of the asset with minimal necessary intervention. An additional comment was made urging the consideration of the circularity of new materials like ultra-high-performance fibre building materials. In the additional comments field, one respondent in Switzerland mentioned that conservative standards often inhibit recycling. Another respondent in Switzerland mentioned that the greatest impact strategies are the processing and reuse of excavated materials and the recycling of concrete. Lastly, one respondent emphasised that the focus should still be on the preservation of existing and the sustainable construction of new structures, without limiting the focus only to damage events.

3.3 Multi-Criteria Assessment

After exploring each circular strategy and perceived impact individually, the authors continued with a multi-criteria assessment (MCA). As demonstrated in Figure 2, out of the four dependent variables of perceived impact for each strategy, three are optimal to maximise (resource savings, GHG savings, and economic benefit), and one is optimal to minimise (effort to implement). Each of these variables was normalised within its range of values so that a score of 1.00 is the optimum of highest resource savings, cost benefits, GHG savings, and lowest effort. The plotting of each of these variables per strategy, with the average of all variables in the red dashed line, is in Figure 3. Similar to results reported previously, Repair holds the highest score with Refurbish at second and Reduce, Recycle, and Re-mine as the next highest strategies.

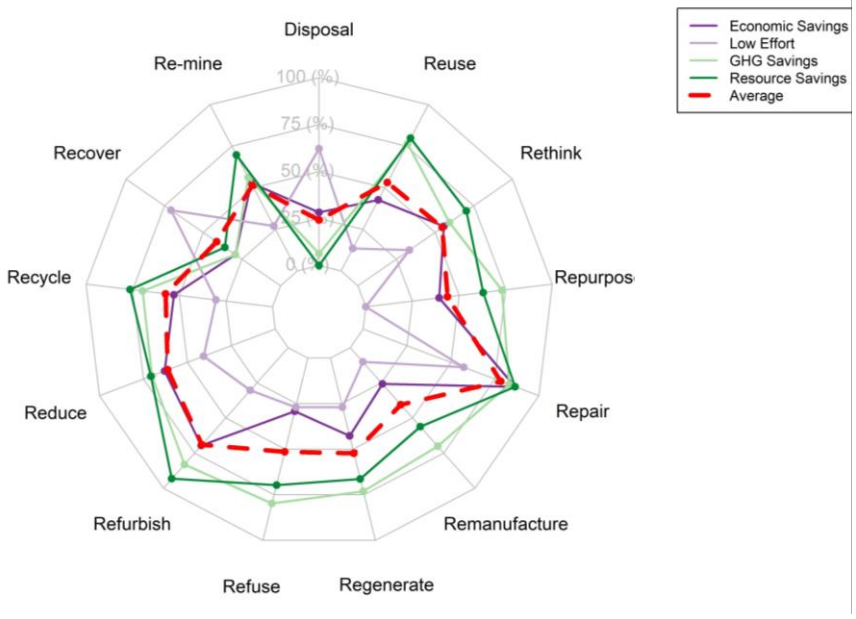

Figure 3. Visualisation of the multi-criteria assessment with the normalised dependent variables of perceptions per circular strategy The dashed red line (Average) shows the average score of the four perceived impacts. Results demonstrate Repair has the best score and Disposal has the worst score of perceived impacts.

Figure 3 was built so that each of the dependent variables was weighted equally, but in the design of the survey, the perceived effort was framed negatively, and the other three variables were framed positively. Figure 4(b) shows the average data reported in Figure 3, but Figure 4(a) shows different results when each variable is weighted differently. Specifically, Figure 4(a) weights the negative variable (perceived effort) equal to the combination of positive variables (perceived GHG savings, resource savings, and economic benefit). This approach is used for a slightly more conservative approach to rank-ordering the strategies. The results show that Repair is still favoured, followed by Refurbish, Reduce, and Recycle. Interestingly, four out of the top five strategies are the same between the different weighting approaches, with Recover and Rethink as the only differences.

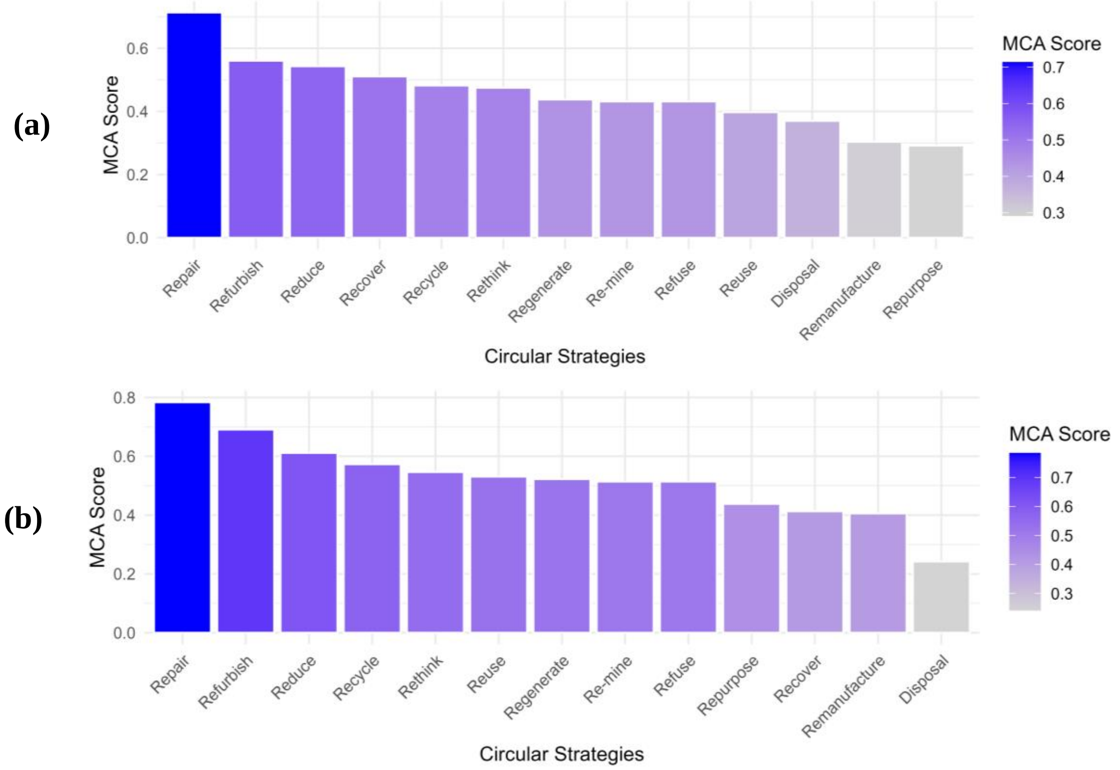

Figure 4. Multi-criteria assessment of circular strategies.. Considering the normalisation of the perception factors with weights of (a) 50% perceived effort, 16.7% perceived resource savings, 16.7% perceived GHG savings, and 16.7% perceived net economic benefit; and, (b) 25% perceived effort, 25% perceived resource savings, 25% perceived GHG savings, and 25% perceived net economic benefit.

4. DISCUSSION & CONCLUSIONS

This research significantly aligns with the United Nations Sustainable Development Goals (SDGs). Foremost, the research aim contributes to SDG 9: Industry, Innovation, and Infrastructure, as building resilient infrastructure can reduce disaster recovery costs and restore the level of service. Maintaining infrastructure is critical to facilitate the additional services of society. SDG 11 focuses on sustainable cities and communities, which is relevant because of the integration of CE principles in an area of industry that produces about 30% of the total waste worldwide (Jin et al., 2019). Specifically, Repair directly addresses SDG 9 by rapidly restoring infrastructure functionality with minimised virgin material input, while Refurbish supports SDG 11 through prolonging asset usability and reducing urban waste. Lastly, the application of CE principles to infrastructure supports SDG 13: Climate Action, because adopting many of the CE interventions for infrastructure management is perceived to reduce GHG emissions and enhance resilience against climate-related disasters.

This study's findings on R-strategies for post-hazard infrastructure reconstruction are exploratory based on perceptions from practitioners working on various asset types in multiple countries, likely reflecting distinct priorities. Regional policymakers tasked with risk management and sustainable development may focus on Reduce or Regenerate strategies that align with long-term resilience and integration with the community, similar to Çetin & Kirchherr (2025). Alternatively, a framework for CE actions by different stakeholders (primarily engineers and contractors) for specific assets finds Repair and Refurbish as the most common strategies, followed by Reduce, Reuse, and Recycle (Coenen et al., 2020). The long lifecycle and often public ownership of infrastructure assets distinguish its lifecycle patterns and R-strategies from other sectors, such as textiles. These unique dynamics emphasise why a systems-level approach to infrastructure management is warranted, along with bespoke strategies based on the contextual properties of both the hazard and infrastructure type.

4.1 Limitations

Methodological limitations are inherent in this research approach. The survey was distributed via multiple methods, including individual emails and postings on LinkedIn. The targeted audience was the US, the UK, and the German-speaking region of Europe, but the responses were not proportionate, nor were there sufficient responses in the sampling for any statistical power to represent a sub-population. In addition, the gender imbalance limits the generalizability of the results. The work was also open in scope of application, specifically not directed toward any particular infrastructure asset or any specific stakeholder related to the construction and operation of infrastructure assets. Future work can dive deeper into specific assets, different geographic locations, or the perspectives of specific stakeholders. Furthermore, collecting more responses can help bring statistical significance to the results.

A common challenge in survey-based research is with survey design. A set of questions asked about the highest level of damage where a circular strategy is currently or could be used, but this makes analysing all applicable strategies difficult. Some participants did not finish the survey out of the belief that, because no sustainable strategy is currently used, especially in the post-hazard restoration process, there is no value gained from the survey. A potential limitation of this work is the framing of the questions themselves. The R-strategies are a dynamic and evolving list that has been synthesised through academic research and do not necessarily reflect what is seen or practiced in industry. Thus, the introduction of new terms to describe existing practices may cause confusion compared to extracting labels of current practices from those surveyed.

This survey aimed at capturing the current state-of-the-art and state of knowledge, and asked about perceptions around different circularity strategies, but the survey did not capture the reasons, the *why*, behind the responses. This could be explored further through in-depth interviews with practitioners. Lastly, this research, because of its exploratory nature, focused on high-level strategies for circularity, but did not explore specific actions as done by Coenen, at al. (2020). Focusing on specific actions or integrating different circularity indices may help facilitate the industry's transition to a CE.

4.2 Future Work

The exploratory nature of this research is a strong starting point to base additional future work that could expand the methodological approach, the analysis, or the applicability. The most straightforward next step would be to continue to collect more survey responses. With a larger population, additional analyses based on demographics and asset type could be explored to reveal more localised trends. Beyond surveys, using interviews can provide more in-depth nuance on each circular strategy, explaining why certain strategies are not adopted or what might be needed to evolve the industry. Preliminary work on circular strategies for post-disaster recovery that did use interviews and workshops was conducted by Çetin & Kirchherr (2025). Their research also calls for additional empirical work on barriers and enablers for adopting circular strategies. A deeper analysis of the economic and ecological trade-offs for each circular strategy relative to traditional approaches could better inform practitioners.

Additional methodological considerations could collect targeted information to develop weights for each factor involved for making a circularity decision, or integrate game theory for waste-management decision making, similar to Palafox-Alcantar et al (2020). These might be evaluated using a qualitative comparison analysis to develop a causal relationship between different conditions. One of these factors could be a CE index, not previously discussed in this work. Using a CE index, like the material circularity indicator, may illustrate the current resource inefficiencies in practice to motivate efforts for adoption. Lastly, this work aims to be the first step in developing guidance for examining how circularity might be integrated into practice. These findings, in combination with further work mentioned above, may be used to develop a rapid audit and circular strategy restoration guide for industry.

4.3 Conclusions and Contributions

This work addresses the lack of research on the application of CE strategies for infrastructure, specifically in the context of post-hazard restoration. Although Disposal is, and will likely continue to be, the most common approach to damaged assets, the study identifies Repair and Refurbish as the most favourable CE strategies, with Recycle and Reduce being the next top strategies with growing interest. Refuse and Regenerate were perceived most often as being not applicable circular strategies in future applications, with Regenerate perceived as having nearly no current application; but Rethink, Reduce, and Recover were perceived to show the most promise for the future. These findings have immediate implications for practitioners who aim to enhance efficiency and sustainability in restoration efforts. The survey results reveal a growing interest among practitioners in adopting a wider range of CE strategies, even for severely damaged infrastructure. This suggests a readiness within the industry to shift towards more sustainable practices, indicating potential for broader adoption and integration of CE principles.

The aim of this work is to be a first step towards developing decision support for practitioners by highlighting the current lack of practical tools and frameworks. Overlaying R-strategies thinking into current practices can begin to align actions for optimal use of infrastructure. Keeping materials in use for as long as possible through appropriate circular strategies in post-hazard contexts may prove to be economically and environmentally advantageous. This work stands to be a call for further research in this direction and provides many opportunities for future work in the combination of circularity and restoration of infrastructure assets for increased resilience through climate action for sustainable cities and communities.

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AUTHOR CONTRIBUTIONS

Brandon S. Byers – Conceptualisation, Methodology, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing;
Dan Bompa – Conceptualisation, Methodology, Writing - Original Draft, Writing -Review & Editing, Funding acquisition;
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DATA AVAILABILITY

The anonymised survey data is available at the following location: https://doi.org/10.3929/ethz-b-000726176

DECLARATIONS

Competing interests - The authors declare no competing interests.

APPENDIX

The aggregated results of the current use at a certain damage state were averaged per strategy, and the current use versus suggested future use are compared in Figure A1 below. The figure indicates that existing strategies should be considered for more severe damage, and strategies not yet heavily implemented should also be considered.

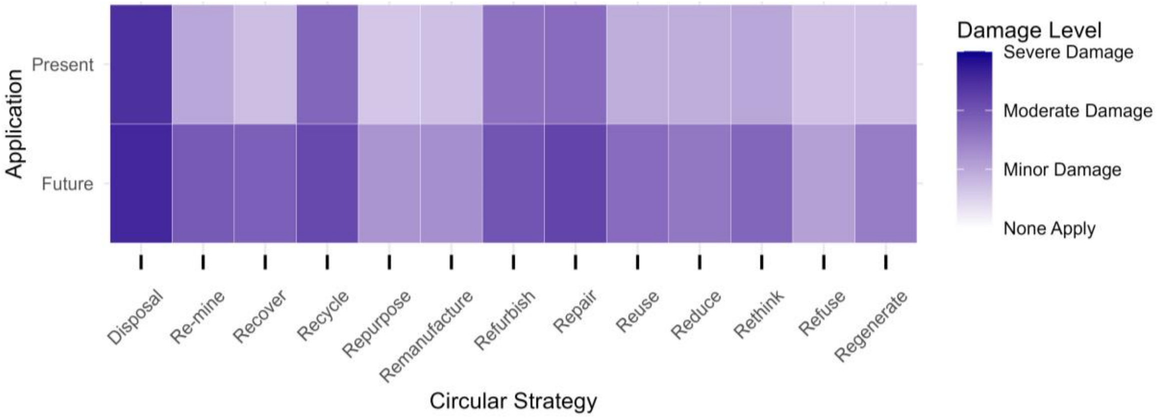

Figure A 1. Current and suggested future applications of circular strategies by averaged damage level

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