Integration of Carbon Emissions Estimates into Climate Resilience Frameworks for Transport Asset Recovery

Stergios A. Mitoulis[1], Dan V. Bompa[2](✉), and Sotirios Argyroudis[3]

[1] Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham, UK

[2] School of Sustainability, Civil and Environmental Engineering, University of Surrey, Guildford, UK

d.bompa@surrey.ac.uk

[3] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge, UK

Abstract. This study describes a framework for optimizing environmental sustainability, climate resilience, and cost in post-hazard transport asset recovery. Particular focus is given to the environmental impact assessment component and its conceptual integration with resilience metrics. After describing the workflow adopted in the complete framework, the environmental impact modelling assumptions, system boundaries, and life cycle inventories for materials, on-site activities and transportation are detailed. Carbon equivalent emissions are evaluated for various restoration tasks for a bridge subjected to nine flood scenarios and represented through a sustainability index. A baseline environmental impact analysis is initially conducted, considering conventional materials, construction techniques, and procedures for each restoration task. Additional sensitivity studies are carried out to evaluate the influence of low-carbon solutions and task duration on carbon emissions. These are weighted based on the probability of the bridge being in a specific damage state. The results demonstrate that low-carbon solutions can provide carbon savings to varying degrees depending on the hazard intensity. Normalised sustainability, resilience, and cost metrics are combined into a unique global index, which can be adopted to prioritise the recovery of the asset. Suggestions on adopting circularity indicators and waste hierarchy levels into such frameworks are also given.

Keywords: Sustainability · Climate Resilience · Circularity · Metrics · Transport

1 Introduction

The built environment consumes 50% of raw materials, contributing to 36% of global energy use and 39% of energy related CO_2e emissions [1]. Infrastructure assets are the backbone of a sustainable society, integrated into a system of systems. The smooth operation of these systems is essential for the functioning and development of society.

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Physical assets are increasingly vulnerable to various threats such as natural or man-made hazards, as well as prone to degradation from mechanical and/or environmental loading during service. Enhancing the resilience of such assets is instrumental to ensuring the continuity of essential services. Engineering resilience can be defined as the ability of an asset, or network, to withstand and restore swiftly from low-frequency high-impact events that change its capacity and function.

Sustainability is deeply ingrained in all aspects of infrastructure development and management. Evaluation of the performance metrics encompassing environmental, economic, and social considerations, have become integral for assessing the sustainability of the infrastructure assets and networks through their life cycle. In construction, the environmental component is typically considered through life cycle assessments (LCA) and is addressed below. Circularity involves transitioning from a conventional linear resource flow to a circular model. Restoration and regeneration represent a step forward, assuming a shift from an anthropocentric perspective to an eco-centric approach for a resilient environment. Restoration of physical assets requires resources, whilst restoration of the environment implies avoiding natural resources depletion.

This paper presents a case study describing the restoration of a transport infrastructure asset, specifically a bridge subjected to various flood scenarios, while considering sustainability and circularity. This is carried out through assessments of carbon emissions, resilience, and cost, as well as adoption of qualitative approaches for circularity.

2 Integrating Environmental Impact into Resilience Frameworks

This section summarises a framework that incorporates LCAs into climate resilience frameworks, through the global warming potential (GWP) category (in tCO_2e) and in a proposed a global metric (I_{SRC}). The global metric includes resilience, environmental sustainability, and cost. In this paper only a brief description of the framework, conceptual plots for sustainability and resilience, and the GWP assessments are described.

The conceptual plots depicted in Fig. 1 pertain to the scenario wherein a critical transport asset is impacted by a significant stressor, such as a flood, and appropriate measures are taken to reinstate its capacity and functionality. Figure 1 serves as an illustration of the benchmark case, while in Ref. [2], instances of ex-ante and ex-post restoration of well and poorly maintained assets are presented, respectively. Figure 1a shows the upfront (solid lines) and ancillary tCO_2e (dashed lines) resulting from the construction (as exemplified by paths OA) and maintenance of the asset throughout its lifespan. In all cases, the ancillary tCO_2e are demonstrated to exceed the upfront emissions due to the diversion of traffic during maintenance and restoration. Figure 1b, on the other hand, presents the resilience curves of the asset. The magnitude of resilience (R index) [3], denoted by the area under the resilience curve, is evaluated as a metric between the occurrence of the hazard event (t_e) and the completion of recovery at time t_h. Sustainability encompasses the entire lifespan of the asset.

With regard to characteristic points and paths the following definitions are considered in Fig. 1: O–construction starts, A–construction completed/asset operational, AB–bridge operates with minimal maintenance/inspection, A'B'–greenhouse gasses (GHG) increase due to decrease in bridge functionality and traffic detours, BE–idle time due to no action taken post-hazard, B‘E’–GHG rapidly increase due to bridge closures and traffic diversion, EF–restoration measures are implemented, E‘F’–supplementary GHG due to restoration and traffic detour, FH–asset in normal operation, F‘H’–same as A‘B’. In Fig. 1b, the resilience has a small drop due to e.g., deterioration effects, which could be due to the corrosion of tendons and traffic increase. The gradual loss of bridge functionality may lead to occasional detours, and hence tCO2e, which are shown with line A‘B’ in Fig. 1a. The figure refers to the case where a hazard leads to a significant loss of asset performance, and a rapid increase in tCO2e between B‘E’ and at a smaller rate after the restoration of the bridge commences (point E in Fig. 1b). After the completion of the recovery, no additional direct tCO2e, and a small increase in indirect tCO2e (see F‘H’), similarly to A‘B’, occurs.

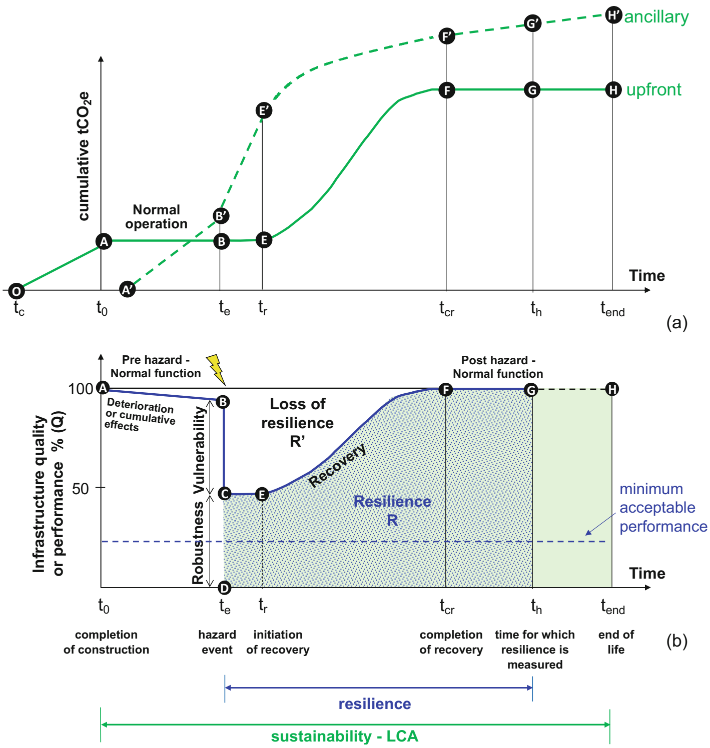

Fig. 1. Conceptual plots of sustainability and resilience for a baseline scenario without regular maintenance (a) evolution of GHG, and (b) resilience represented as the performance of transport asset responding to a hazard occurrence [2].

The framework includes the assessment of resilience, sustainability, and cost parameters in eight steps. First, (i) hazard intensity measures (IM) are defined based on predicted, measured, or estimated hazard data (e.g., high-resolution flood maps to deduce probabilistic relationships of established IM). These are then used to (ii) evaluate the vulnerability of the asset using fragility functions. The curves correlate the probability of exceeding given damage states (i.e. minor, moderate, extensive, severe/complete) with the hazard IM. After evaluating the fragility functions, (iii) the asset recovery is evaluated based on restoration (structural capacity) and reinstatement (traffic capacity) models. Subsequently, depending on the damage states, (iv) the GHG emissions are assessed using the procedures described in detail in this paper. The resilience (v) corresponding to the structural capability of the asset to withstand a hazard occurrence of different damage states for a given IM is then evaluated using a probabilistic approach. This is then transformed into a resilience index (R).

GHG emissions are evaluated for various restoration strategies and written in as relative measures in a sustainability index (S). For the latter, the cumulative tCO2e of the asset under recovery at a given time t after the start of restoration, are considered. The index considers the cumulative tCO2e of the asset under recovery and is weighted based on the probability of the asset being in a specific damage state and the temporal evolution of GHG per damage state. The latter depends on the emissions per restoration task (see details below). Finally, (vi-viii) the sustainability and resilience indices are optimised using a multi-criteria decision-making approach (e.g. Pareto fronts), and a cost index is evaluated afterwards. These are aggregated in the global metric (I_{SRC}) [2]. The framework and global metric are tested using a standard river crossing bridge that has three spans and is exposed to different flood scenarios [3–5].

3 Environmental Impact Assessments

3.1 Environmental Impact Modelling

Evaluation of the environmental impacts of a product or process, including production, transportation, and disposal, is typically conducted using life-cycle assessments (LCA) [6]. For civil engineering works, this is typically expressed in the Global Warming Impact (GWP) category through a carbon-equivalence tCO2e of all GHGs. Depending on the assessment method, the whole-life carbon is divided into embodied and operational components [6, 7]. Embodied carbon refers to the GHG incorporated in construction materials, processes, and activities [8]. Operational carbon refers to the GHG emissions during the service of a building or asset.

To evaluate the environmental impacts for the main restoration tasks, GWP measured in tCO2e was considered. The assessment includes GWP due to fossil emissions, as for construction works the biogenic emissions are insignificant, and can be disregarded. The system boundaries adopted here correspond to a ‘cradle-to-practical completion’ approach (A1–A5). The emissions are divided into the following groups: (i) the upfront emissions, correspond with the carbon for the works included in the restoration tasks at the stages shown below; and (ii) the ancillary emissions refer to traffic re-routing or pavement degradation, among others.

The data flows are assessed per restoration work and use established functional units for materials and processes, e.g., 1.0 m^3 for concrete or 1.0 kg for steel. These are subsequently converted into carbon emissions, based on the estimated bills of quantities and corresponding carbon equivalent factors listed in Table 1. The assumptions for estimating quantities and equipment use are in Sect. 3.2. The construction equipment fuel consumption rate is based on manufacturer datasheets. The emissions are assessed by multiplying the bill of quantities ($Q_{i,m}$) with the corresponding embodied carbon factor ($F_{i,m}$) and a scalar factor to account for the restoration task duration ($\lambda_f = 1$ for mean durations). The subscript i indicates the material or process, whilst subscript m is for the life-cycle phase (materials, onsite activities, or transport).

A baseline analysis is conducted first. This includes in-situ concrete with cement as the only binder and new reinforcing and prestressing rebars. The same strategies are analysed with low-carbon solutions to minimise emissions for carbon-intensive tasks. This reduction is achieved by replacing materials from virgin sources with low-carbon materials and using biofuel blends for construction equipment. The main conventional construction materials are substituted by low-carbon alternatives including fly ash and GGBS in concrete. Steel rebars and tendons contain 97% recycled steel obtained through electric arc furnace production. The baseline analysis assumes mineral diesel, while the low-carbon alternative assumes a biofuel blend. It is assumed that the transportation distance is 25 km and uses a diesel articulated HGV (>3.5 - 33t - average laden). Transporting people and construction equipment is not accounted for.

Table 1. Life cycle inventory.

Conversion factors	$kgCO_2e$/unit	Conversion factors	$kgCO_2e$/unit
Concrete C25/30 - CEM 1	0.142/kg	Fibreglass	1.540/kg
Concrete UK C25/30 (25% GGBS)	0.130/kg	FRP	5.000/kg
Steel rebar global avg	2.289/kg	Epoxy	5.700/kg
Steel rebar UK 97% recycled EAF	0.835/kg	Rubber	2.660/kg
Stone	0.138/kg	Bearings	1.630/kg
Timber (sawn)	0.587/kg	Water supply	0.344/m^3
Portland cement, CEM I	0.860/kg	Diesel (100% mineral) *	3.314/l
Mineral aggregate	0.003/kg	Diesel (biofuel blend) *	3.156/l
Asphalt	0.380/kg	Electricity UK	0.233/kWh
PVC pipe	2.560/kg	Articulated diesel HGV	0.776/km

* Equipment consumption from datasheets (l/h); RT Crane 45T (18.2); Barge B < 20m (6.0), JX Piling Rig (7.0) Cat 325 1.5 CY backhoe (23.2), Generic 5HP diesel water pump (0.80, Compressor Kaeser Honda G360 (6.0), Cat D7 Dozer (34.0), Asphalt mixer 16HP (9.2)

3.2 Restoration Tasks

A three-span river-crossing bridge with shallow foundations is considered for this assessment (Fig. 2a). The fragility curves (Fig. 2b) and restoration models (Fig. 2c) were taken from previous research [4, 5], correspondingly, for four damage states (minor, moderate, extensive, severe). Nine scour depths ranging from 1.0 to 5.0 m with a step of 0.5 m were analysed. Only one pier foundation was scoured. These scenarios lead to a sequence of restoration tasks (R), for various damage states: minor (1, 11, 12, 14, 5), moderate (1, 11, 6, 12, 14, 16, 15, 5), extensive (1, 11, 6, 12, 14, 2, 16, 5, 15), and severe (1, 11, 6, 12, 14, 2, 5, 16, 15, 23). Below, the task ID is followed by the name, weighing factors for damage states (minor/moderate/extensive/severe), and the description of materials and processes.

- R1 Armouring countermeasures and flow-altering/cofferdam (0.70/0.80/0.90/1.00) pre-dredging, driving the support piles, bracing, 35 m diameter cofferdam with UBP 305 × 305 × 223 struts, sheet piles, and temporary works, fuel, transportation, and consumable materials.
- R2 Temporary support per pier (0.70/0.80/0.90/1.00) two temporary support frames incorporating UC 305 × 158 columns and UB 1016 × 305 × 494 beams, and associated platforms, consumables, installation and disassembly, transportation.
- R5 Repair cracks and spalling with epoxy and/or concrete (0.50/0.70/0.85/1.00) scaffolding, removal of 50 mm of concrete, new concrete, resurfacing, new parapets, drainage pipes, consumables, on-site activities, transportation, demolition waste.
- R6 Re-alignment and/or levelling of pier (0.50/0.70/0.85/1.00) assembly and disassembly of temporary frames, scaffolding, consumables, transportation.
- R11 Erosion protection measures (0.70/0.80/0.90/1.00) excavation, manufacturing and assembly of gabions, steel and stone materials, intervention measures cover both riverbanks, upstream, and downstream for 50 m, transportation.
- R12 Rip rap and/or gabions for filling of scour hole and scour protection (0.70/0.80/0.90/1.00) riverbed compaction, rip-rap placement and compaction, transportation of materials and some excavated soil within the site.
- R14 Ground improvement per foundation (0.70/0.80/0.90/1.00) excavation around the foundation, installation of a 2 m deep compacted gravel layer, associated materials and consumables, support system as for R2, transportation.
- R15 Installation of deep foundation system (1.00/1.00/1.00/1.00) 16 piles of 800 mm diameter and an RC pile cap of 3.5 × 5.5 × 1.5 m with a gross longitudinal rebar ratio of 4%, materials, on-site activities, transportation, temporary frames.
- R16 Extension of foundation footing (1.00/1.00/1.00/1.00) footing extension on all sides by 2 m over a depth of 1.5 m, some concrete removal, formwork, materials, transportation, demolition waste.
- R23 Demolish/replacement (part) of the bridge (1.00/1.00/1.00/1.00) a pier, and two decks are being replaced, thus R1, R18, 19, and R22 are considered.

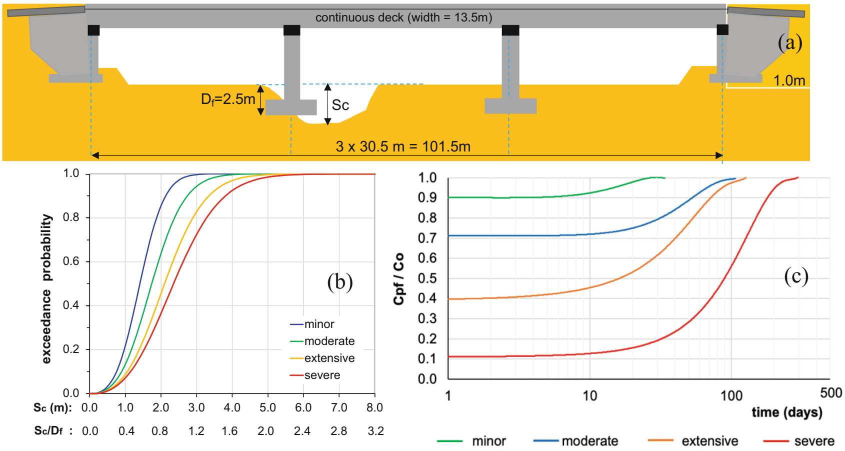

Fig. 2. (a) The reference bridge of the case study, (b) fragility curves of the bridge as a function of the scour depth (Sc) and the normalised Sc / D_f (D_f: foundation depth), (c) restoration curves of the bridge as a function of time (C_{pf}: post-flood capacity, C_o: original capacity) [2].

4 Results and Discussion

4.1 Environmental Impact

According to Table 2, tasks with more temporary works and fewer new materials (R1 and R2) have similar emissions from materials and equipment fuel consumption. Tasks with more new concrete and rebars have higher emissions from materials (R16). The literature shows that around 80% of the emissions are associated with materials extraction and production, which is similar to the average of the baseline analysis [9]. Both assessments assumed the same duration for all restoration tasks, regardless of the materials used. It is assumed that the use of low-carbon materials does not affect task duration and that these materials are available from the same manufacturers as conventional materials. Changes in task duration can impact on-site emissions, but materials and transportation remain constant. Longer construction tasks and associated materials can lead to 50% higher emissions due to higher fuel consumption (R1).

Figure 3a and Fig. 3b illustrate the weighted tCO2e per damage state and restoration task (R_i), using the weighting factors described in the previous section. Figure 3a corresponds to the conventional restoration strategies, whereas Fig. 3b refers to the low-carbon restoration approach. It is noted that for R23 the maximum values 1986 and 860 are given in the graphs, as these well exceed the max value of the tCO_2e axis. It is observed that conventional and low carbon strategies have similar emissions for R1, R11, R12, R6, R2, R14, and R5, with differences up to 15%. For R16, R15, and R23 significant differences were observed varying from 40% to 57%.

Table 2. Environmental impact assessment results.

Task	Conventional materials (tCO_2e)	On-site activities (diesel) (tCO_2e)	Transportation (diesel) (tCO_2e)	Total (tCO_2e)	Low carbon solution[(1)] (%)	Influence of duration[(2)] (%)
R1	16.9	63.6	0.1	80.6	−14.9	± 49.8
R2	2.7	4.9	0.1	7.7	−9.6	± 30.6
R5	18.3	1.1	1.2	20.6	−17.6	± 3.8
R6	3.4	0.7	0.1	4.2	−13.4	± 7.5
R11	645.5	29.0	3.5	678.0	−4.6	± 1.7
R12	21.7	2.5	0.1	24.3	−1.0	± 6.1
R14	29.0	5.0	0.3	34.3	−1.3	± 7.0
R15	235.0	113.9	0.4	349.2	−38.3	± 10.5
R16	346.5	16.2	0.2	362.9	−57.4	± 1.7
R23	1867.1	112.8	5.7	1985.6	−56.7	−3.3

(1) replacement of main construction materials and fuel with low-carbon alternatives;
(2) increase/decrease of carbon corresponding to the use of onsite equipment and machinery [2].

Close inspection of the emissions divided by materials, on-site activities, and transportation, indicate that materials can account for 21% to 99% of the emissions, with an average of 74% for all activities. On-site activities can represent 2% to 100% of the emissions, while transportation is up to 6%. Some restoration tasks have similar values to those found in the literature (i.e. construction activities contribute to 30% of the total, and transportation is around 4%). The environmental impact of traffic diversion due to structure closure can be significant in relation to the restoration of the asset [10].

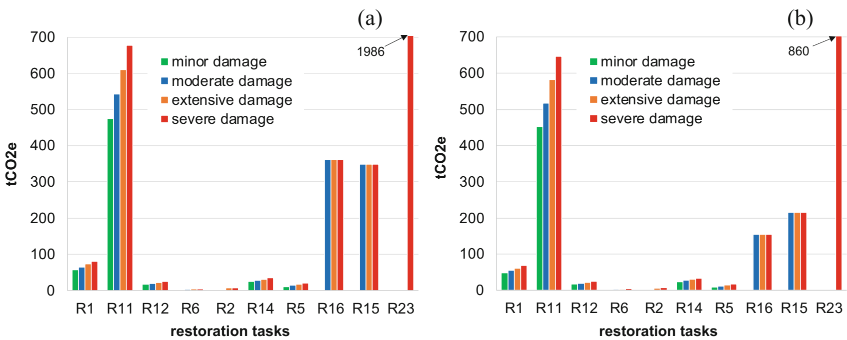

Fig. 3. (a) Weighted tCO2e per damage state and restoration tasks (R_i) for (a) conventional restoration and (b) low carbon restoration.

Normalised tCO_2e versus the resilience index R relationships for the nine scenarios examined, indicate that the highest emissions are for a scour depth of $S_c = 5.0$ m, whilst the lowest for $S_c = 1.0$ m. For the low-carbon case these are always smaller than for the conventional case, as expected. The differences in tCO2e are slightly smaller at lower hazard intensities and are higher by up to 60% for higher hazard intensities (e.g. $S_c =$ 5.0 m). Regarding the sustainability index (S), this is 1.0 for low hazard intensity and low carbon solutions and increases with hazard intensity and use conventional materials.

Assuming various weighing cost factors (>1.0) for low-carbon materials, it is shown that the cost of the greener solution is up to 20% higher on average. However, the low carbon restoration strategy results in a 50–60% decrease in total tCO2e, encouraging the use of more sustainable solutions. For this case study a realistic hazard curve (peak flow versus return period) was adopted based on closed-form solutions available in the literature. Curves considering an increase in peak flow discharge due to climate change potential were also investigated [2]. Note that the results from this paper are specific for the case study and include expected uncertainty in LCA modelling due to assumptions outlined in Sect. 3.

4.2 Circularity Considerations

In asset restoration, the primary objectives revolve around minimizing the environmental impact caused by the interventions. Whilst this reductionist sustainability approach has its merits, using a circular approach in such interventions will enable quicker regeneration of the environment. In the built environment, circularity includes three main principles: (i) durability, referring to building and elemental service life planning, (ii) adaptability, the extension of the service life of the asset as a whole; and (iii) waste reduction and high-quality waste management, as well as future circular reuse of components and parts, or high-quality recycling of elements following deconstruction.

The effectiveness of implementation of circularity is typically assessed through indicators. In buildings, there are three sub-indicators for circularity: material, product, and system circularity [11]. Whilst circularity tools exist for buildings, there are limited assessment tools to ascertain the level of circularity in infrastructure [12]. These papers looked at design input, resource availability, adaptability, and reusability, highlighting the importance of circularity indicators in transport infrastructure projects.

As future directions, in the case of post-hazard interventions in asset restoration, the rehabilitation strategies could adopt circularity approaches. Specific indicators and decision trees based on circularity hierarchy levels can be developed for systematic decision-making. These could include the potential for reinstatement/rehabilitation, routes for harvesting components, and exploring upcycling/reuse in structures. Temporal-scale dependent life-cycle assessment would need to be carried out according to relevant asset functionality phases.

5 Conclusions

This paper described a framework for optimizing environmental sustainability, climate resilience, and cost in post-hazard transport asset recovery. The focus was on integrating the environmental impact assessment with resilience metrics. The conceptual framework and the environmental modelling assumptions were first provided. Carbon equivalent emissions were evaluated for various restoration tasks for a bridge affected by nine flood scenarios, considering conventional and low carbon solutions. After normalizing them into a sustainability index, these were combined into a global index with resilience and cost. Circularity considerations were also given.

The results show that restoration tasks with more temporary works and fewer new materials have relatively low emissions, in comparison with tasks that are materials intensive. Materials can account for 21% to 99% of the emissions. On-site activities can represent 2% to 100% of the emissions, while transportation is up to 6%. Low carbon solutions can provide up to 57% carbon reductions, at an increase in cost of about 20%. Longer construction tasks can lead to a 50% increase in emissions due to higher fuel consumption by construction equipment. Close inspection of the normalised emissions versus the resilience index for the nine scenarios indicated that the highest emissions are for the highest scour depth, whilst the lowest emissions for the lowest depth.

These results give an indication of the environmental impact of post-hazard interventions in transport asset recovery, and the suggested metrics can be adopted to prioritise asset recovery. The circularity indicators and hierarchy levels mentioned provide further insight into enabling more sustainable interventions that align with the wider planetary recovery drivers.

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