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Sustainability and resilience-driven prioritisation for restoring critical infrastructure after major disasters and conflict

Nadiia Kopiika [a,c,*], Roberta Di Bari [a], Sotirios Argyroudis [b,c,d], Jelena Ninic [a], Stergios-Aristoteles Mitoulis [a,c,d]

[a] University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[b] Department of Civil and Environmental Engineering, Brunel University of London, Kingston Lane, Uxbridge Middlesex, UB8 3PH, UK
[c] bridgeUkraine.org, London, UK
[d] MetaInfrastructure.org, London, UK

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A B S T R A C T

Considering the extensive destruction of infrastructural systems worldwide during conflicts, human interventions, climate exacerbations and other disasters, there is urgent need for efficient strategies to facilitate well-informed decisions for infrastructure restoration based on integrated resilience and sustainability. Despite extensive destruction and impact of human interventions, reconstruction prioritisation frameworks for such regions remains underexplored, which has predominantly focused on climate-related hazards. We argue that this gap in the literature creates immense challenges for war-torn countries seeking to align their efforts with external donors and global development goals. This paper introduces a novel framework for planning the recovery of bridge portfolios in conflict-affected regions, using a scoring system that incorporates integrated resilience and sustainability metrics. The framework is applied to a case study of ageing bridges in Ukraine, demonstrating its effectiveness in guiding strategic investment allocation for infrastructure recovery that balances proactive and reactive measures in conflict zones.

1. Introduction and state of the art

1.1. *Proactive maintenance is of paramount importance in infrastructure management*

Critical infrastructure, plays a key role in the economic and social well-being of regions and countries. In particular bridges, as important components of transportation networks, facilitate the mobility of people and goods, and their function is crucial for the maintenance of essential services and emergency response in the event of unforeseen disasters (Esmalian et al., 2022; Liu et al., 2019; Ouyang et al., 2024). Bridges are exposed to various hazards and threats that can compromise their structural integrity and functionality, leading to serious consequences for communities and economies(Forcellini and Mitoulis, 2024). For example, the recent collapse of the Francis Scott Key Bridge in Baltimore resulted in economic losses of $15 million per day due to the closure of the Port of Baltimore and claims to insurers of approximately $3 billion (Al Jazeera and News Agencies, 2024).

Along with other critical infrastructure entities (e.g., airports, dams, pipelines, and nuclear facilities), bridges are often highlighted among the most vulnerable to human-induced threats (Stewart, 2010), including terrorism, shelling and missile attacks in conflict-

* Corresponding author.
E-mail address: n.kopiika@bham.ac.uk (N. Kopiika).

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prone regions, impacting local and global safety and security (Kopiika et al., 2025). Although this type of hazard has not been sufficiently investigated in the international literature, it can lead to catastrophic consequences, with the most typical being disruption of transportation networks, loss of life, and significant economic damage (Hay et al., 2019). Bridge damage of varying degrees leads to different functional capabilities and refurbishment costs. Such damage affects the structural integrity of bridges and their load-bearing capacity, often necessitating traffic restrictions or closures to mitigate safety risks that are central to maintaining the performance of regional infrastructure (Argyroudis et al., 2020).

Critical infrastructure, in particular bridges, in conflict zones face distincts damage mechanisms compared to natural disasters. Direct blast impacts can cause immediate failures, such as deck collapse, pier cracking, and severed load-bearing elements. Secondary effects, like fire-induced material weakening or shockwave vibrations, may worsen damage, leading to progressive collapse (Lua et al., 2014; Tokal-Ahmed, 2009). Prolonged conflicts also impose stressors like overloading from military vehicles and neglected maintenance, resulting in material fatigue. Understanding these mechanisms is vital for designing reconstruction strategies that address immediate restoration needs while ensuring long-term resilience against recurring stressors.

In addition, ageing infrastructure and inadequate maintenance practices contribute to the deterioration of bridges over time, increasing vulnerability to structural defects and potential failure. For example, corrosion of steel reinforcement, deterioration of concrete and fatigue cracking are common problems that can jeopardize the safety and serviceability of bridges if not addressed promptly and effectively (Kramarchuk et al., 2022, Kopiika et al., 2021; Blikharskyy et al., 2021; Domaneschi et al., 2024a; Kopiika et al. 2024a). Therefore, the combined impact of general deterioration as a result of years of operation and the high risk of extensive destruction of bridges in conflict regions underlines the importance of proactive risk management and resilience planning to ensure optimal investment in infrastructure maintenance and rehabilitation (Mitoulis et al., 2021; Achillopoulou et al., 2020). Both proactive adaptation and post-conflict recovery of bridge portfolios should be thoroughly planned and organised, taking into account the critical importance of each asset to the functionality of the transport network (Sun and Zhang, 2020). This underscores the growing need for an integrated framework that supports the informed reconstruction of bridge portfolios in response to conflict-related hazards by combining conflict-aware resilience and sustainability metrics.

Advancements in monitoring and control technologies, such as structural health monitoring systems (Domaneschi et al., 2024b), dynamic response analysis for seismic resilience (Hu et al., 2024), and real-time predictive modelling (Mitoulis et al., 2022), have significantly improved transport infrastructure resilience by enabling proactive management and informed disaster response. These innovations offer valuable insights for integrating monitoring systems into conflict-aware reconstruction strategies, enhancing both proactive and reactive decision-making.

1.2. Resilience and sustainability metrics facilitate bridge recovery

Effective restoration and maintenance of critical infrastructure requires a comprehensive understanding of both resilience and sustainability metrics. These metrics provide key insights into the ability of structures to withstand and recover from adverse events, as well as the societal, environmental and economic impacts of their adaptation and rehabilitation. By incorporating resilience and sustainability considerations into the decision-making process, stakeholders can prioritize rehabilitation actions that not only improve the durability and reliability of infrastructure but also minimize sustainability impacts and optimize resource allocation.

Resilience metrics provide a framework for assessing a bridge's ability to withstand and recover from damage caused by adverse events, including conflict-related events (Shaban and Makhoul, 2023; Argyroudis, 2022). These metrics take into account factors such as robustness, redundancy, resourcefulness and rapidity. Robustness evaluates the structural integrity of bridges under various stress factors, while redundancy ensures that alternative routes or systems can compensate for any loss of functionality (Pitilakis et al., 2016); Argyroudis et al., 2019). Resourcefulness reflects the capacity to efficiently mobilise resources in response to damage, and rapidity measures how quickly a bridge can be restored to operational status. These metrics are essential for informed decision-making in post-disaster recovery, especially in conflict-induced regions (Fang et al., 2022), Mitoulis et al., 2023a). They enable the prioritisation of bridges that are vital for maintaining essential connectivity, ensuring that limited resources are allocated where they are most needed (Mitoulis et al., 2024; Kopiika et al. 2024b).

Resilience itself, hence, involves reducing the likelihood of failure, minimising the consequences of such failures, and ensuring rapid recovery Bruneau and Reinhorn, 2007; Lebel et al., 2006; Walker et al., 2004). In conflict zones, infrastructure vulnerability increases, with disruptions to transportation routes severely affecting supply chains, humanitarian aid, and evacuation routes. In these context, resilience assessments must account not only for direct functionality losses but also for indirect socio-economic impacts, such as those caused by traffic detours and delays (Ayyub, 2014). A cost-based resilience index that includes these factors is essential for accurately gauging the resilience of infrastructure (Argyroudis et al., 2020; Shaban and Makhoul, 2023; Argyroudis, 2022; Mitoulis et al., 2023b). Prolonged periods of hostilities highlight the pressing need for proactive adaptation measures, such as enhancing blast resilience, incorporating greater redundancy in critical systems, and implementing rapid recovery strategies to address intentional damage(Mitoulis et al., 2023b). Strengthening infrastructure resilience before damage occurs is crucial in conflict-affected regions, where proactive approaches that enhance redundancies and/or increasing resource allocation can significantly reduce damage and enhance the capabilities in reconstruction to pre-empt disruption. Key measures include adopting modular and prefabricated bridge designs, for rapid deployment and localised repairs, and reinforcing critical structural components, such as piers and abutments, with advanced materials like ultra-high-performance concrete to improve resistance to blasts (Williamson, 2010; Dusenberry, 2010). Furthermore, comprehensive management plans, including vulnerability assessments and prioritization of critical transport corridors, enhance the ability of infrastructure networks to endure and recover from conflict-induced disruptions.

Sustainability metrics, on the other hand, focus on the long-term environmental, societal and economic impacts of both bridge failure and restoration efforts. In conflict-induced regions, where resources are often scarce, sustainability considerations are crucial to ensure that proactive mitigation and reactive restoration efforts contribute to the broader goals of regional stability and development Fanchiotti and Szarzynski, 2024; UNISDR, 2015; Ide et al., 2023. Sustainability metrics in the economic dimension assess the direct and indirect economic impacts of bridge failure and restoration, including the costs of construction, the economic losses due to disrupted trade and transportation, and the benefits of restored connectivity (Kurth et al., 2020). By quantifying these factors, decision-makers can allocate resources efficiently, focusing on restoring infrastructure that will most effectively boost economic recovery and resilience (Farahmand et al., 2024; Liu et al., 2021). However, in case of hostilities, the restoration of critical infrastructure often prioritises economic recovery and stability, while environmental concerns are overlooked (Chan et al., 2019). Hence, metrics such as carbon footprint, energy consumption, and resource utilisation are vital for assessing the sustainability of different restoration strategies, guiding the selection of materials, technologies, and methods that minimise environmental impact while maximising infrastructure longevity and resilience. On the other hand, proactive adaptation of infrastructure might help to reduce the risk of adverse events. Societal metrics that evaluate the potential impact of bridge failure on civilian casualties or displacement are essential for prioritising proactive adaptation measures to minimize human risk in conflict-prone areas. Bridges that are strategically significant for civilian safety, such as those used in evacuation or emergency response routes, hence, receive higher priority.

Thus, sustainability metrics, such as those derived from the Life Cycle Sustainability Assessment (LCSA), offer valuable tools for assessing the environmental, economic, and social impacts of infrastructure adaptation (Henzler et al., 2020). These metrics can guide decision-making, ensuring that mitigation efforts not only meet immediate needs but also contribute to long-term sustainability. In conflict-prone areas, traditional lifecycle models often fall short due to their static and deterministic nature, which fails to account for the uncertainties and frequent hazards that can drastically alter infrastructure outcomes. To address these challenges, it is essential to adopt dynamic, scenario-based approaches that integrate sustainability metrics early in the planning process (Di Bari et al., 2019; Di Bari et al., 2020a). This ensures that restoration strategies are not only resilient but also aligned with sustainable development goals (UN, 2015)), reducing the risk of future conflicts driven by resource scarcity and environmental degradation Fanchiotti and Szarzynski, 2024; UNISDR, 2015). The considerations highlighted above underscore the pressing need for a comprehensive approach towards well-informed decisions that goes beyond traditional assessment methods, incorporating a broader range of factors that impact the overall sustainability and resilience of infrastructure systems.

1.3. Purpose, motivation, and novelty

Bridges, as the important components of transport infrastructure, are among the primary targets of terrorist attacks in conflict-prone regions, leading to their substantial destruction and crucial socio-economic consequences. Considering the enhanced risk of human-induced destruction of these critical assets worldwide, there is an evolving need for efficient strategies to facilitate well-informed decisions for their restoration based on integrated conflict-aware resilience and sustainability metrics. Frameworks for resilience and sustainability assessment, available in the international literature, predominantly focus on climate and natural hazards. However, the destruction of infrastructural assets during hostilities poses unique issues, e.g., violated supply, humanitarian, and evacuation corridors, as well as challenges in restoration due to increased downtime, limited access and safety issues. Moreover, the global recovery of bridges across the region should account for a range of factors in the prioritization process. These include the national importance of the bridge, the presence of alternative routes, average daily traffic, bridge dimensions, significance for emergency evacuation, its role in border crossing, possible negative consequences for the social sector and the environmental impact of its failure –just to name some (Sohouenou et al., 2021; Morelli and Cunha, 2021; Gao et al., 2024; Chen et al., 2024). All these aspects, in conjunction with typically limited resources available during global post-conflict recovery, necessitate a different novel framework to foster efficient resilience and sustainability-driven infrastructure recovery. The prioritisation of bridge importance, as the major

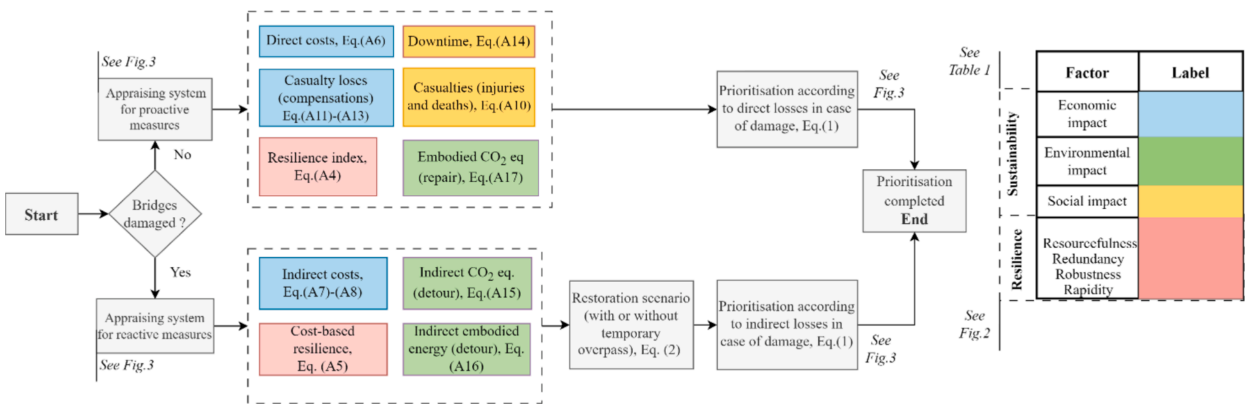


Fig. 1. The general overview of the prioritisation for proactive and reactive measures, based on resilience and sustainability factors. The three dimensions of sustainability impact, covered in the paper are indicated with colours: blue-economic, yellow-social, green-environmental (see Table 1). Resilience components are shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

outcome of the framework, can aid in the effective allocation of limited resources, endure unforeseen challenges, and contribute to the long-term sustainability of transportation systems. Hence, the main motivation of this paper was to develop such a framework, to fill this significant gap of knowledge. In this research, we propose a unique scoring system, which involves a synthesis of conflict-informed resilience and sustainability metrics and enables priority-based categorisation of bridges. By incorporating a comprehensive methodology that combines existing research with novel methods, metrics and insights, this framework introduces a pioneering approach towards resilience- and sustainability-driven infrastructure restoration in conflict-prone regions.

2. Integration of sustainability and resilience metrics in the reconstruction of damaged infrastructure to conflicts

2.1. Methodological approach

Conflict-induced damages to infrastructure severely compromise its operability, with substantial economic, environmental, and societal consequences. Addressing these impacts requires comprehensive strategies that integrate sustainability and resilience into the planning and restoration processes, ensuring that infrastructure can withstand future challenges and support sustainable development in conflict-affected regions. Resilience and sustainability, while different concepts, have commonalities and often intersect in the assessment of bridge systems (Marchese et al., 2018). Fig. 1 illustrates the main interconnections between dimensions of sustainability impact and resilience attributes, which are integrated into the prioritisation strategy for the restoration of large portfolios of infrastructural assets, in particular, bridges. Hence, the flowchart (Fig. 1) outlines a decision-making process for prioritising proactive and reactive measures in bridge infrastructure, using a combination of resilience and sustainability factors. This framework is relevant for regions which are currently facing ongoing conflicts or are potentially prone to them, e.g. regions with political disputes, ethnic tensions, territorial disputes, religious conflicts, or competition over resources.

The process begins with an assessment of whether the assessed conflict-prone region was affected by human-induced attacks, leading to substantial infrastructure degradation (e.g. extensive damage to a large portfolio of bridges). If the investigated region has not yet experienced such circumstances but remains at risk of conflict, the framework is then employed to prioritize proactive measures to enhance infrastructure resilience against potential threats. The detailed description of such proactive measures is out of the scope of this paper but may include the following: enhancing the structural resilience of bridges (e.g., implementing blast-resistant design features, multiple load-bearing paths, use of durable materials), introducing enhanced monitoring systems (e.g., real-time monitoring with sensors or drones); arrangement of physical barriers, camouflage and concealment strategies, etc. Given that these measures demand substantial material, human, and time resources, efficient cost allocation is crucial and should be based on a prioritization process. Priority should be assigned to bridges whose failure would likely result in the most severe economic (see ***blue*** colour in Fig. 1), social (***yellow*** colour), environmental (***green*** colour) consequences, or resilience-related (***red*** colour).

While prioritising bridges for proactive measures primarily focuses on direct losses from potential bridge failures—such as casualties, costs, and environmental impacts of restoration—reactive measures consider future indirect losses due to bridge closures, like environmental and economic challenges from detours. These time-dependent prioritisation factors help identify which assets are most critical for maintaining infrastructure operability, making them the top priority for restoration. A more detailed explanation of the resilience and sustainability metrics, along with the unique scoring system that integrates them, is provided in the following sections.

2.2. Resilience assessment of aged bridges to conflict-induced damage

Previous studies (Argyroudis et al., 2020; Argyroudis. 2022) have focused mainly on the resilience assessment of bridges subjected

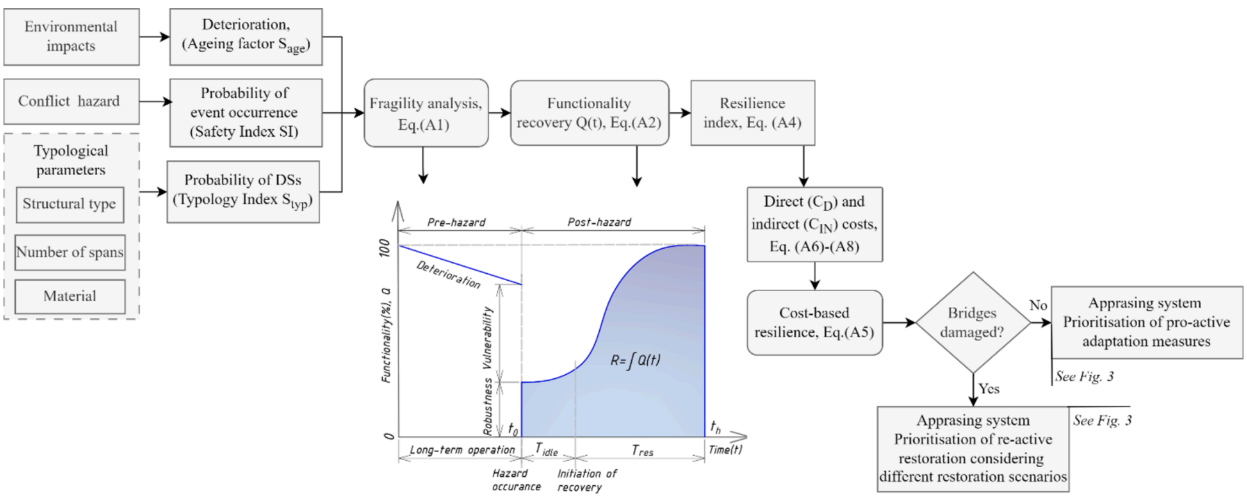


Fig. 2. Resilience-based factors for prioritisation of proactive adaptation measures and reactive restoration measures.

to natural hazards, which cannot be used for human-induced threads, a significant gap, covered in our research. Also, in this paper, we go beyond the current state of the art by presenting a framework that incorporates both resilience and sustainability metrics to facilitate prioritisation in restoration endeavours. In particular, resilience metrics are assessed according to the approach, presented in Fig. 2.

The fragility of bridges in conflict-induced regions in a broader context is associated with their vulnerability to blast. These blast loads, resulting from explosions caused by accidents, acts of terrorism, or military conflicts, can have devastating consequences, including structural damage, functional impairment, or even catastrophic failure. In this paper, we utilise existing literature to quantify the fragility of various bridge types under blast loadings (reflected through "Typological parameters" in the workflow above). The response of each bridge to an explosive impact is influenced by a unique set of external factors (such as the explosive material, stand-off distance, charge weight, angle of incidence, height of detonation, and presence of barriers) and internal factors (including structural characteristics like material properties, stiffness, mass, ductility, redundancy, and continuity) (Tokal-Ahmed, 2009; Williamson, 2010; Sammarco, 2014; Olmati et al., 2016). In this paper among the external factors the stand-off distance is considered as the crucial one in assessing vulnerability (Lv, et al., 2023; Ding et al., 2017; Roy and Matsagar, 2021). To address this, our research employs a Safety Index to account for the likelihood of close stand-off distances in blast scenarios (e.g., the higher the possibility of close detonation, the lower the Safety Index SI).

In this study, internal factors will be analysed through a typological classification (e.g., structural type, number of spans, material composition, etc., as illustrated in Fig. 2) to assess each type's vulnerability to blast loads. Although each bridge design possesses unique structural characteristics, it is reasonable to assume that bridges with similar configurations, materials, and dimensions will demonstrate comparable failure mechanisms. These shared characteristics enable the assignment of typology indexes (S_{typ}) to groups of bridges, a process detailed further in Section 3.2. The general assumptions and relevant studies regarding these factors are outlined below.

(i) **Material.** Heavier structures typically demonstrate greater blast resistance, as increased mass reduces velocity and, consequently, the energy that must be absorbed through strain (Dusenberry, 2010). Also, concrete structures, particularly under close-in detonations, outperform steel structures, which are more susceptible to local instability due to the complex stress combinations in slender members (Lua et al., 2014).

(ii) **Number of spans.** Bridges with greater continuity and redundancy tend to localise damage rather than experience a global collapse, preserving the structural integrity and preventing the lateral propagation of damage to adjacent sections. The progressive collapse occurs when a local failure in a primary structural element triggers a chain reaction of failures. Therefore, structural continuity, redundancy, and energy-dissipating capacity are vital for redistributing loads from the damaged area to adjacent regions capable of bearing the additional stress without collapsing (Tokal-Ahmed, 2009; Williamson, 2010; Sammarco, 2014; Olmati et al., 2016; Roy and Matsagar, 2021). In this context, bridges with more spans and alternative load paths have a lower risk of progressive collapse.

(iii) **Typology.** Among different bridge types, arch bridges are considered more blast-resistant due to their inherent geometry. The curved design of arch bridges allows them to distribute and absorb blast forces more effectively, enhancing their structural robustness against explosive impacts.

The vulnerability of bridges was evaluated here considering two factors: (i) general deterioration of its capacity due to ageing effects; (ii) damage caused by human malicious interventions (e.g. explosions). Damage is characterised based on Damage States (DS) depending on severity and extent as follows: intact (DS0), slight damage (DS1), moderate damage (DS2), extensive damage (DS3) and collapse (DS4) (Argyroudis et al., 2020). The novel approach proposed in this study assesses conflict-induced damage to each asset by considering both the likelihood of extreme events based on the asset's proximity to regions of intense hostilities (such as the line of demarcation) and the probability of reaching or exceeding various Damage States (DSs) depending on the bridge's typology. These elements are integrated into the proposed framework through the use of a Safety Index (SI) and a typology index (S_{typ}). Furthermore, the framework also accounts for the impact of ageing on the infrastructure, incorporating it through the ageing factor (S_{age}).

While the general gradual approach towards resilience assessment is given in Fig. 2, the equations, taken from recent studies (Argyroudis et al., 2020; Shaban and Makhoul, 2023; Lua et al., 2014; Decò et al., 2013; Dong and Frangopol, 2015) are given in Annex A. The measurement of environmental and economic metrics takes into account requirements and calculation rules established in international standards (ISO 14,040 and ISO 14044 for environmental metrics, ISO 15686 for economic metrics). The functionality recovery of the bridge from different damaging scenarios in this workflow is assessed based on the resilience curve (See Fig. 2), according to Eq. (A2). To measure the ability of a structure to absorb and recover from the damage intensity, described by the damage state, the resilience index R is used, as per Eq. (A4). Based on this, the loss of resilience can be measured against the resilience of the perfectly resilient asset ($R = 1$), minus the estimated resilience index (Argyroudis et al., 2020). R measures the asset's resilience in terms of its functionality and assesses the direct losses resulting from partial or complete bridge failure. However, the loss of bridge functionality will lead to limited or complete disruption of communication routes and, hence, indirect losses, including those resulting from detoured traffic or business interruption. Since the reduction in resilience does not directly measure the economic losses (both direct and indirect), the cost-based resilience index R_C is utilised, incorporating socio-economic impacts (direct and indirect losses) into the resilience evaluation (Argyroudis et al., 2020; Shaban and Makhoul, 2023) see Eq. (A5). This encompasses the calculation of direct costs (C_D), required for bridge restoration and indirect losses (C_{IN}) due to vehicle operation on a detour and vehicle time loss (as per Eq. (A6)-(A8)). Losses due to disruption of the railway route (for railway bridges) are not considered in this workflow.

Given the critical role bridges play in a country's supply chains, their disruption during ongoing hostilities significantly exacerbates the negative consequences of their failure, particularly due to the restricted access for both lightweight vehicles and trucks. Therefore, the temporary overpasses are widely used, as an enabling strategy to reduce indirect losses due to the required detour. In this study, we consider this impact by evaluating two restoration scenarios: with or without a temporary overpass, which influences the rapidity of restoration of the route and finances allocation during post-conflict recovery.

2.3. Bridge damage impact on sustainability

The impact of structural damage on sustainability is evaluated considering metrics of societal, environmental, and economic performance, such as cost (direct C_D and indirect C_{IN}), downtime DT, casualties N_c (including number of injuries and deaths), additional energy E due to traffic detour, Greenhouse gases (GHG) emissions calculated with CO_2 equivalent due to both detour and repair works (embodied impacts). These metrics are described in detail in Table 1. As can be seen from the table, some of the parameters, that can be used for the assessment of sustainability consequences of bridge damage and/or failure have already been introduced within the cost-based resilience indication (e.g. C_D, C_{IN}, DT).

The selected sustainability metrics are primarily calculated as the product of a certain quantity and the impact per unit (for example, embodied CO_2 eq. is calculated by multiplying material quantities in volume and tCO_2 eq. per volume unit). A comprehensive overview on the equations used for the measurement of sustainability metrics is provided in Annex A.

Economic impacts are calculated based on requirements and calculation rules established in ISO 15686. Cost information is derived from cost databases and historical data.

Environmental sustainability metrics in this study include indirect impact such as the required energy ($E_{\_D}$) and GHG emissions (CO_2 eq. CO_{2_D}) from detours as well as the embodied CO_2 eq. from repair and refurbishment works on the bridge (CO_{2_R}) in accordance to ISO 14040, ISO 14044. Indirect impacts were assessed by Eq. (A16)-(A17) (Padgett and Tapiaб 2013; Dehghani and Shafieezadeh, 2019), considering the traffic on the detour and its length (in km) and CO_2 eq. per km (average emission of traffic due to cars, truck and other vehicles). Embodied environmental impacts for each quantity are derived from available environmental databases for constructions, such as Environmental Product Declarations (EPDs), valid for the considered geographical context, according to ISO 14025. If these are unavailable for the geographical context, average environmental datasets are selected from the literature (see Annex A). The assessment of indirect and embodied environmental impacts of repair processes is a rather challenging task, considering the uncertainty of bridge response to the hazard. Predicting the specific components of each bridge that will be damaged and the extent of damage requires comprehensive structural analysis and detailed design work, which is beyond the scope of this paper. Therefore, the embodied and indirect environmental impacts of repair processes are estimated using expert judgement and asset dimensions as outlined in Eq. (A17).

The approach followed here for the preliminary quantification of social consequences is based on previous studies (Ellingwood and Wen, 2005; Padgett and Li, 2016) in terms of mean damage index, mean injury and death rate given the occurrence of each damage state (DS). The relationship between limit state and damage/injury rate is presented in Table A.1 (Ellingwood and Wen, 2005) in Annex A.

The unified metric for sustainability losses, associated with different dimensions (e.g. economic, societal) could be used in the policy, to enable more efficient allocation of resources. Hence, the direct and indirect monetary losses due to the disruption of transport routes and necessary restoration works are already widely used to prioritise investments. However, these monetary losses do not account for societal consequences in terms of possible causalities, which, should be a dominant factor in proactive measures, aiming to minimise the risk of bridge failures. In this research we propose to use the casualty losses (CL), which in monetary dimensions describe

Table 1
Sustainability metrics reflecting impacts on the economy, society and environment.

Dimensions	Metrics	Units	Description
Economic	Direct cost (C_D), Eq. (A6)	€	Costs required for restoration of bridge + temporary overpass arrangement (time-independent)
	Indirect costs (C_{IN}), Eq. (A7)- (A8)		Economic losses due to needed traffic detour (time-dependent)
Socioeconomic	Value of statistical life (VLS), Casualty losses (CL), Eq.(A11) –(A13)	€	Costs due to casualties caused by bridge failure/damage (amount of compensation)
Societal	Downtime (DT), Eq. (A14)	days	Period during which the access to structure is limited or impossible due to disrupted traffic route
	Injuries (N_I) Eq. (A10)	number	Possible number of injuries due to bridge failure/damage
	Deaths (N_D), Eq. (10)	number	Possible number of deaths due to bridge failure/damage
Environmental	$E_{\_D}$, Eq. (A16)	MJ	Indirect impact (energy consumption) because of bridge closure and required detour (time-dependent)
	CO_{2_D}, Eq. (A15)	tCO_2 eq.	Indirect CO_2 eq. because of bridge closure and required detour (time-dependent)
	CO_{2_R}, Eq. (A17)	tCO_2 eq.	Embodied CO_2 eq. emissions due to repair and refurbishment works on the bridge

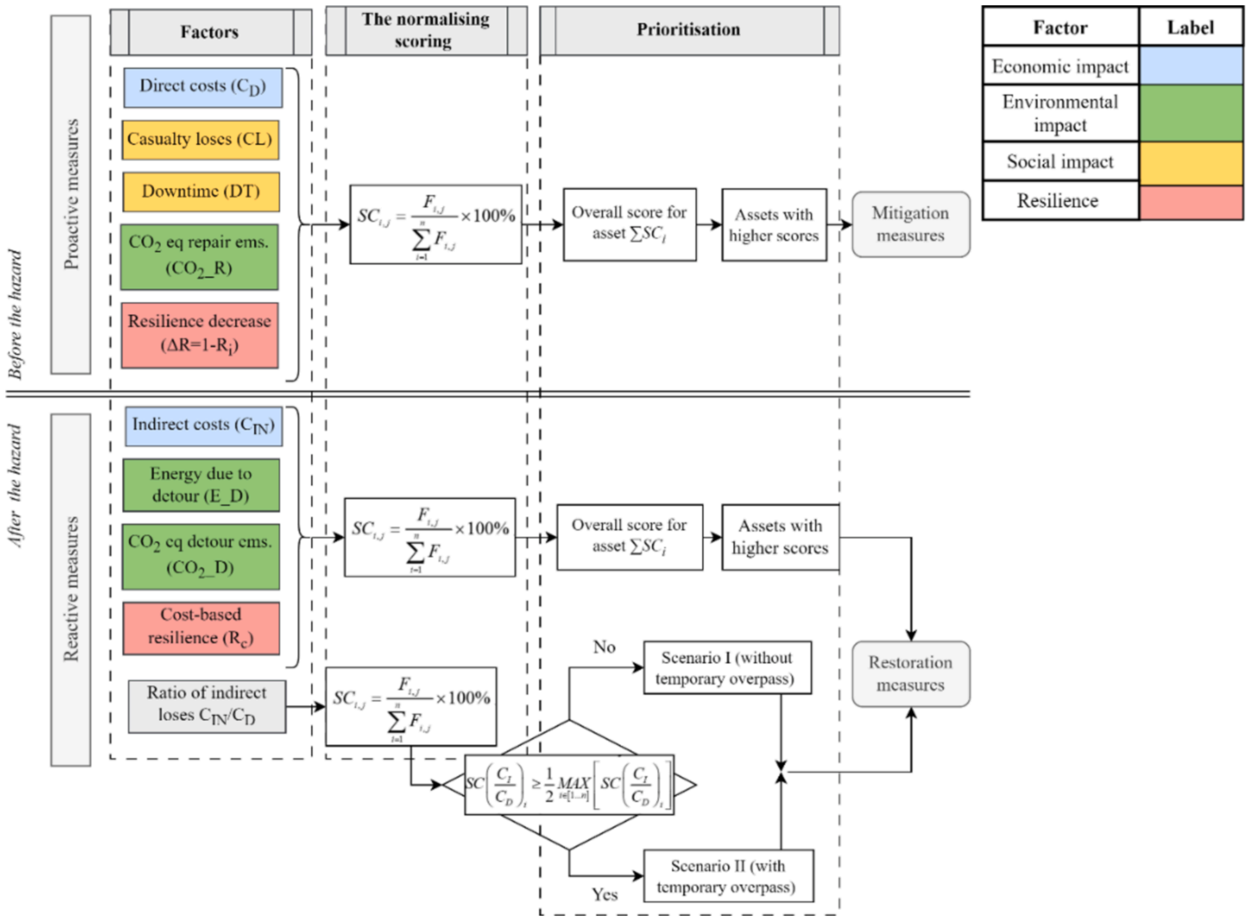


Fig. 3. The framework for integrating sustainability and resilience metrics to prioritise proactive mitigation and reactive restoration measures for critical infrastructure.

the societal consequences of bridge failure. Casualty losses are obtained by summing the potential amount of compensation, which will need to be paid in case of injury or fatality. For each individual, this can be obtained considering the Value of a Statistical Life, −VSL (Andersson and Treich, 2011). Such a term could be claimed as controversial since the evaluation of human life could be considered inappropriate as it should be priceless. However, the assessment of the value of human life is necessary for the implementation of policies adequate to modern conditions, including compensation frameworks and strategies to enhance safety and reduce risks (Kartashova et al., 2019)). This procedure relies on the human capital approach, which estimates the value of a person's life based on their statistical market productivity and the benefits derived from reduced mortality (Andersson and Treich, 2011). The particular equations for VSL are given in Annex A (Eq. (A11) to (A13)) (Kartashova et al., 2019; Kuchyňa, 2015; Pratt and Zeckhauser, 1996; Office of the Secretary of Transportation, 2016). The number of casualties (injuries N_I and deaths N_D) entails the estimation of the loss ratio (LR) and injury/death indexes (I_I, I_D) and is calculated with the use of Eq. (A10). It is important to consider that the evaluation of statistical life is associated with sensitive issues and, thus, should be used only for preliminary comparative estimation of the social impact of bridge failure. More detailed research in this direction is required, yet, it is out of the scope of this paper.

Other societal metrics are e.g., the downtime (DT), which is the period during which the access and use to the structure are limited after the hazard occurrence, and this is estimated by Eq. (A14). This parameter is also further used for the assessment of the environmental consequences of bridge closure and the required detour.

2.4. Adaptation prioritisation based on sustainability and resilience − a novel framework

Strategic planning of mitigation and restoration efforts in conflict-prone regions require analysis of diverse sustainability and resilience-based factors to maximise the efficiency of investments for adaptation. Hence, there is a pressing need for a unified framework to support resilience- and sustainability-driven prioritisation of infrastructure recovery in conflict zones. The scoring system proposed in this research (see Fig. 3) considers chosen metrics reflecting environmental impacts, social considerations, economic consequences, and the ability of the asset to withstand and recover from disruptive events.

By integrally evaluating this cumulative impact of these factors, decision-makers can: (i) prioritise actions and proactive measures, aimed at mitigating risks and (ii) support well-informed reactive measures during global rehabilitation of the region. In addition, by early introducing proactive mitigation strategies, the risk of asset failure and its consequences can be minimised leading, though, to eliminating the necessity of future reactive measures (as there will be no or minimal damage to asset).

Proactive measures involve pre-emptive actions taken before the damage to the bridge occurs, and their prioritisation is based on overall consequences to critical sectors to mitigate potential risks to the infrastructure. On the other hand, **reactive** measures are taken in response to actual damage inflicted on bridges during conflicts. These measures focus on swift assessment, repair, and restoration of the bridge infrastructure to minimise disruptions to transportation networks and ensure the safety of users. Reactive measures may involve deploying rapid assessment teams, mobilising resources for immediate repairs and implementing temporary solutions (overpasses) to restore functionality until repairs can be made.

In this research, we propose to distinguish all the impacts of asset failure into time-independent ("anyway"-losses) and time-dependent indirect losses, which will increase impact during the restoration process, when the bridge is closed and hence the traffic is disrupted. Hence, ***proactive measures*** herein account for the direct loss when the bridge fails or is damaged and this includes: direct repair costs (C_D), casualty loss (CL), downtime (DT), embodied CO_2 eq emissions and emissions due to repair (CO_{2_R}). Resilience values are here taken into account to give the bridges, failure of which will lead to higher consequences for the infrastructure higher priority in proactive adaptation strategies. Considering the ***post-failure rehabilitation scenarios (reactive measures)***, they need to account for indirect time-dependent impacts, which often significantly exceed the direct loss (e.g. indirect costs (C_{IN}), indirect CO_2 eq. emissions (CO_{2_D}) and energy ($E_{\_D}$) because of bridge closure and required detour). Also, the socio-economic impacts of bridge closure are accounted with the cost-based resilience index R_c. Thus, in such cases, the most efficient restoration scenario should be chosen, to ensure optimal cost allocation and minimise losses. During post-conflict recovery of the region, the highest priority, thus, should be given to assets whose closure would result in higher indirect time-dependent losses.

This framework proposes the use of the scoring (rating) system, integrating disparate resilience and sustainability metrics in a global score for each one of the assets. The normalising technique is used to reduce the score for a given factor to a dimensionless value (Vafaei et al., 2016; Arya et al., 2010). Such an approach enables comparison and weighting with similar normalised scores for other factors, and the weighted scores are then summed to obtain an overall score for the asset. Thus, assuming the scores for a particular factor for assets [1…n] are [F_1…F_n], respectively then the normalised score for each of i-th asset is defined by:

$$SC_{i,j} = \frac{F_{i,j}}{\sum_{i=1}^{n} F_{i,j}} \times 100\% \tag{1}$$

where j corresponds to the number of factors in the system.

According to this method, the bridge, in that causes the greatest impact will receive the highest score in the prioritisation strategy. The normalised scores, being dimensionless, allow flexibility in adjusting scores within the three sustainability dimensions (environment, economic, and social) and some of the resilience attributes (see Fig. 3). This novel scoring technique, thus, enables to prioritise bridges within the large portfolio when developing either proactive mitigation (PSC_i, see the upper part of Fig. 3) or reactive restoration (RSC_i, see the lower part of Fig. 3).

Also, for decision-making on the optimal restoration (with or without temporary overpass) we propose to use the normalised score value of C_{IN}/C_D to identify assets, for which the indirect losses prevail within the case study. Thus, if the particular bridge has the SC

(C_{IN}/C_D) exceeding half of the maximum score within the case study then its failure will lead to very high indirect losses. Therefore, for this bridge, the restoration scenario II should be chosen to minimise indirect losses. This criterion is described by the equation:

$$SC\left(\frac{C_{IN}}{C_D}\right)_i \geq \frac{1}{2}\underset{i\in[1\ldots n]}{MAX}\left[SC\left(\frac{C_{IN}}{C_D}\right)_i\right] \tag{2}$$

where [1…n]- the number of bridges in the portfolio.

By combining proactive and reactive measures, operators can enhance the resilience of bridges in conflict-prone regions. Proactive measures help reduce vulnerabilities and prepare infrastructure for potential threats, while reactive measures enable rapid response and recovery in the case of bridge damage or failure. Moreover, the approach, described in this study can be potentially applied to a wider range of threads (not only conflict-induced), with the vulnerability models adopted for each particular hazard. Together, these approaches contribute to maintaining critical transportation links and safeguarding the infrastructure essential for the well-being and mobility of communities in affected areas.

3. Application

3.1. Case study: The portfolio of bridges in Ukraine

The application of the novel framework, introduced in this paper is demonstrated with the use of a case study of Ukrainian transport infrastructure, which is subjected to substantial degradation and damages caused by general ageing and conflict-induced hazards (Analytical portal: Economy, 2024). In particular, about 81 % of Ukraine's bridges were built before 1981, and many have surpassed their 60-year lifespan. These structures have faced significant environmental impacts, such as corrosion, fatigue, climate effects, and increased traffic loads, leading to deterioration. Many of them were designed with codes which today are outdated as they do not meet current load and dimension requirements. Research shows that only about 14 % of Ukrainian bridges are satisfactory; the rest are marginally safe under reduced traffic conditions (UA radio news, 2024). In addition, the ongoing conflict has exacerbated the deterioration of bridges, highlighting the need for resilient restoration strategies that can withstand future stressors. The conflict has severely impacted Ukraine's infrastructure, with bridges being particularly affected due to their strategic importance for transportation and commerce(Build, destroy, repeat - battle over bridges and runways in Ukraine, 2023; Economical truth, 2024). They have become primary targets due to their role in facilitating logistics and regional connectivity (Build, destroy, repeat - battle over bridges and runways in Ukraine, 2023; Rice, 2022). Bridges in this region are vital for military operations, obstructing transportation routes, and evacuating civilians through humanitarian corridors (see Fig. 4, Online source 1, 2024; Online source 2, 2024), which underscores the impact of these failures on the resilience and sustainability of the region. Illustrating how the proposed sustainability and resilience-driven framework can mitigate current damage and address future risks is particularly pertinent, highlighting the significance of this case study.

In this paper, the proposed framework is applied to a portfolio of the 18 largest bridges in Ukraine (see Table 2), each holding significant strategic, economic, and social importance.

Spanning the Dnipro River, these bridges ensure the connection between eastern and western Ukraine, which in case of disruption could isolate entire regions, hindering the movement of people, goods, and services. In major cities such as Kyiv and Dnipro the collapse of key bridges would lead to massive traffic congestion, overwhelming alternative routes and paralysing the city's transport network. Additionally, all the bridges included in this portfolio are essential for the transportation of goods, both within Ukraine and in international trade. Their failure would disrupt supply chains, increase transportation costs, and delay deliveries, with severe repercussions for industries and commerce. Furthermore, bridges located in conflict-affected regions, such as Mykolaiv, Kherson, and

a) b)

Fig. 4. The sustainability impact of the bridge in social dimensions. The role of bridges in Ukraine for the evacuation of civil population and for maintaining lifeline supplies to regions in Ukraine and evidence of their destruction: (a)-satellite image (Online source 1 (2022)); (b) evidence from crowdsourcing (Online source 1 (2022)).

Table 2
Portfolio of 18 largest bridges in Ukraine.

No	Bridge name, City	Coordinates	Year of constr. (repair)	L/W (m)	Type*	Daily traffic vehicles /day **	Detour length***
1	Petrivsky bridge, Kyiv	50.4837°,30.548°	1945 (2005)	1430/5	T-MS-S	24,717	1.42
2	Darnytsky bridge I, Kyiv	50.416°, 30.586°	1949	954/15	A-MS-C(S + RC)	24,717	2.57
3	Kryukiv bridge, Kremenchuk	49.053°, 33.424°	1949	1700/8	T-MS-S	1825	30.08
4	Marefa-Kherson bridge, Dnipro	48.467°, 35.083°	1951	1627/5	A-MS-RC	8270	4.81
5	Preobradgensky bridge I, Zaporizha	47.846°, 35.086°	1952	560/15	A-MS-RC	5917	5.52
6	Preobradgensky bridge II, Zaporizha	47.821°, 35.075°	1952	228/15	A-1S-RC	5917	8.39
7	Paton bridge, Kyiv	50.427°, 30.582°	1953	1543/21	G-MS-S	24,717	5.32
8	Antoniv bridge I, Kherson	46.676°, 32.796°	1954	514/6.7	T-MS-S	2326	1.35
9	Amur bridge, Dnipro	48.488°, 35.028°	1955 (2002)	1395/15.5	T-MS-S	8270	4.51
10	Southern Bug bridge, Mykolaiv	46.987°, 31.964°	1964 (2004)	750.7.15.7	G-MS-RC	4001	52.71
11	Metro bridge, Kyiv	50.443°, 30.565°	1965	682.6/28	A-MS-RC	24,717	3.68
12	Central bridge, Dnipro	48.477°, 35.057°	1966 (2019)	1478/21	G-MS-RC	8270	4.46
13	Northern bridge, Kyiv	50.491°, 30.536°	1976	816/31.4	CS-1P-C(S + RC)	24,717	1.45
14	Kaidatsky bridge, Dnipro	48.501°, 34.968°	1982 (2019)	1732/26	G-MS-RC	8270	6.27
15	Antoniv bridge II, Kherson	46.670°, 32.720°	1985	1366/25	G-MS-RC	2326	12.44
16	Southern bridge, Kyiv	50.395°, 30.589°	1990	1256/41	CS-1P-C(S + RC)	24,717	2.23
17	Southern bridge, Dnipro	48.410°, 35.097°	2000	1248/22	G-MS–C(S + RC)	8270	6.26
18	Darnytsky bridge II, Kyiv	50.416°, 30.586°	2010	1066.2/ 43.8	A-MS-C(S + RC)	24,717	2.57

* Individual indexes were assigned to each of the assets, according to following coding scheme: 1st- structural type (T-truss, A-arch, G-girder, CS-cable-stayed,); 2nd –number of spans (MS-multi-span, 1S-one span, 1P-one pylon (for cable-stayed)); 3rd –material (S-steel, RC-reinforced concrete, C(S + RC)- combined (2 materials)).

** Approximate values of daily traffic, based on local traffic conditions and the population of each city (assuming that the daily traffic corresponds to 5% of the city population).

*** Approximate values obtained from Google Open Street maps.

Zaporizhzhia, are key strategic assets. Their failure would significantly impede military mobility, leaving certain regions vulnerable to attacks or occupation, obstructing evacuation routes, and delaying the delivery of humanitarian aid. Finally, due to their substantial size and complexity, these 18 bridges would require extensive restoration efforts in the event of a failure, leading to severe economic, social, and environmental consequences. Table 2 provides details about 18 assets, included in the analysis. Visual illustration of different typologies of the 18 assets is presented in Annex B.

3.2. Vulnerability analysis

The vulnerability of bridges in this study is estimated by considering the following factors, which determine the probability of reaching or exceeding a particular DS by the assets under assessment:

- **deterioration** due to environmental impacts during long-term operation of bridges (depending on age of bridge);
- **probability of occurrence of hazard** of particular intensity measure (IM) close to the asset. This is considered to be a function of the proximity of the bridge to the front line, i.e. the region where hostilities are ongoing;
- **probability of reaching (or exceeding) a damage state** at a particular intensity measure depending on the bridge's susceptibility to damage according to its typology, material, and design.

Thus, the probability of blast loading near each asset was evaluated using proximity-based ranging, specifically applied to the group of bridges within the case study. Hence, the safety indexes were calculated as the ratio of each bridge's distance from the

Table 3
Typological and ageing factors considered for the case study.

DS	S_{typ}, structural type		S_{typ}, number of spans		S_{typ}, material			S_{age} (per decade)
	A	T, G, CS	MS	1S, 1P	S	RC	C(S + RC)	
DS1	1	1.025	1	1.05	1.05	1	1.025	1.025
DS2	1	1.05	1	1.1	1.1	1	1.05	1.05
DS3	1	1.075	1	1.15	1.15	1	1.075	1.075
DS4	1	1.1	1	1.2	1.2	1	1.1	1.1

conflict-affected area to the maximum distance within the portfolio (as of as per spring, 2024, see Fig. B.1, Annex B). Based on these proximity-based safety indexes, assets were divided into three safety index zones (SI zones). Thus, high relative proximity to the zone with hostilities resulted in low safety indexes, so the bridge was allocated to the Low Safety Index zone (Low SI). On the contrary, bridges, located far from hostility zones, have high safety indexes (High SI). Three zones are also illustrated in Fig. B.1. Hence, 18 assets in the case study were assigned safety indexes (SI), revealing the likelihood of conflict-induced damage to each bridge. The ranges were the following: Low SI: 0.01–3; Medium SI: 0.3–0.7; High SI: 0.7–1. In this case study of 18 largest bridges in Ukraine, SI of bridges in Kyiv were between 0.9 and 1 (High SI), in Kremenchuk and Dnipro 0.3 to 0.6 (Medium SI), in Zaporizha, Kherson and in Mykolaiv 0.01 to 0.2 (Low SI zone). The bridge B15 (Antoniv Bridge II, Kherson) was used as the reference in the ranking system to understand the impact of location on the probability of high DS occurrence. This bridge is located directly in the conflict area and is completely destroyed (Militarnyi, 2024). Values of $P[DS_i|IM]$ were based on expert judgement and analysis of the local situation in the region of hostilities as for spring 2024 (See Fig. B.1, Table B.1 in Annex B). The vulnerability of bridges to blast loadings was discussed in more detail in section 2.1. Hence, all the bridges, included in the case study were categorised according to structural type, number of spans and material (Table 2). Individual indexes were assigned to each of assets, according to following coding scheme: 1st- structural type (T-truss, A-arch, G-girder, CS-cable-stayed); 2nd-number of spans (MS-multi-span, 1S-one span, 1P-one pylon – for cable-stayed); 3rd-material (S-steel, RC-reinforced concrete, C(S + RC)- combined two materials). The bridge typology was taken into account by introducing typology indexes S_{typ}, which reflected the higher probability of being in a high damage state for assets, which are expected to be more vulnerable to blast loads (see Table 3). The worsening of the condition and a corresponding increase in the probability of being in higher DS for longer operating bridges (built before 2000) were taken into account by introducing the ageing factor S_{age}, similarly to (Argyroudis et al., 2020). The load-bearing capacity was reduced by DC 2.5 % for DS1, 5 % for DS2, 7.5 % for DS3 and 10 % for DS4 per decade before 2000 s (see Table 3). For some of the assets from the list, certain restoration works were made, which were accounted for as a reduction in the operational lifespan by one decade.

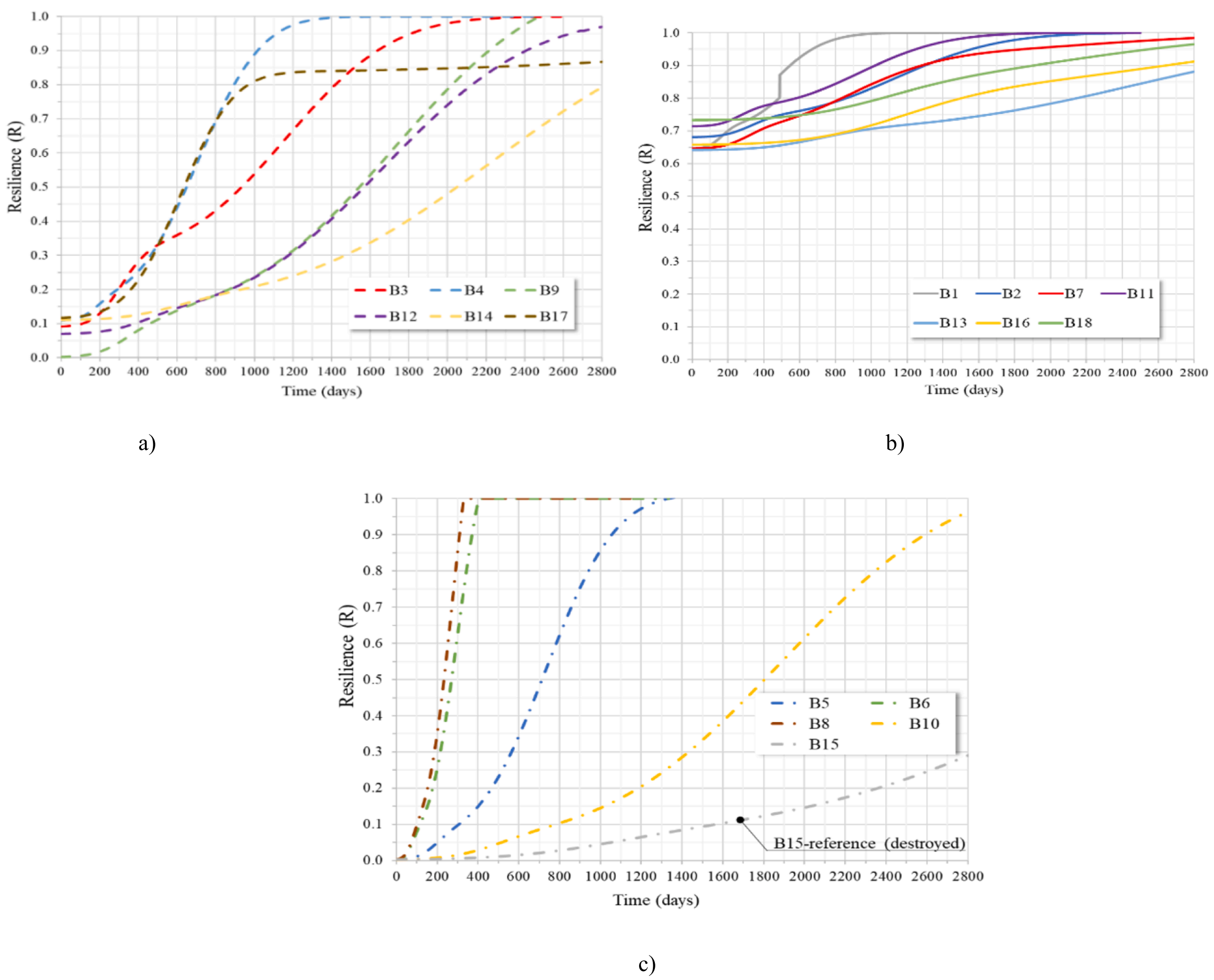


Fig. 5. Resilience curves for assets, depending on their location: (a) high SI zone: B1, B2, B7, B11, B13, B16, B18 (Kyiv); (b) medium SI zone: B3 (Kremenchuk), B4, B9, B12, B14, B17 (Dnipro); (c) low SI zone: B5, B6 (Zaporizha), B10 (Mykolaiv), B8, B15 (Kherson).

3.3. Resilience assessment

The resilience metrics for bridges of the case study were estimated considering the assumed time required for restoration. The detailed repair strategies relevant to explosion and blast-induced damages are not significantly discussed in the international literature, and this issue is out of the scope of this research. Thus, the repair time after each DS was adopted from previous works by assuming probable repair tasks (Argyroudis et al., 2020; Karamlou and Bocchini, 2017) as 90 days/1000 m^2 for full restoration of the bridge (from the total destruction, −DS4). For other damage states, representing partial damages, reduction coefficients were applied (by 10 % for DS3, 25 % for DS2, and 75 % for DS1, based on engineering judgment). Apart from the restoration time, idle time was considered for assets in different locations. In particular, it is important to take into consideration the limited ability (or inability) to begin restoration works on the territories with ongoing hostilities (e.g. in Low SI zone, – in Zaporizha, Kherson, Mykolaiv). In addition to restoration delays, due to the complexity of the organisation of recovery works, the time for inspection of the structure by competent personnel was taken into account. Thus, the reference values of idle time were taken, assuming the need for more time in higher damage states to prepare restoration projects and allocate costs (15 days for DS1, 30, – for DS2, 45, – for DS3, 60, −for DS4) (Argyroudis et al., 2020). The idle time duration was further adjusted based on the safety index to account for the inability to initiate restoration works in regions with ongoing military operations. In this case study, the uncertainty of the recovery process significantly impacts the duration of restoration work. To account for this, a probabilistic model using Monte Carlo simulation was applied to assess the repair duration. The model assumes a cumulative normal distribution for T_{res}, with a standard deviation set at 35 % of the mean, reflecting the stochastic nature and high uncertainty involved. The obtained resilience values, hence, are based on the probability density function of restoration time rather than its mean value. Such an assumption is reliable for the considered case study, due to the high uncertainty in post-conflict recovery scenarios. For other applications, in the availability of more reliable values of the restoration task duration, deterministic approaches could also be considered (Argyroudis et al., 2020). The rate of how quickly each asset achieves a target resilience level at different restoration times could be observed from the R(t) functions (see Fig. 5), which were developed from functionality recovery graphs (See Fig. B.2).

Although, these curves are expected to asymptotically reach full functionality (R = 1), for normalisation reasons the final restoration time was limited to the same value. Thus, the functionality of some assets was not 100 % restored. From the values obtained, it is seen that resilience is highly contingent on the probability of occurrences of DSs, allowing for the grouping of bridges according to Safety Index (SI) zones.

Further analysis of the resilience curves for the three groups reveals the high impact of asset area on the rapidity of recovery. Thus, although bridges located in safe areas (High SI zone) exhibit a similar pattern of R increase, the most rapid resilience recovery is observed for B1 and the most gradual, – for B13, predominantly influenced by the area of these assets. A similar trend is observed for bridges situated in the Medium SI zone, where the slowest R values increase is expected for the B14 bridge (the greatest area). In contrast, the most substantial increase in R was noted for the smallest bridge (B4). For bridges in the zone of the highest risk of destruction (Low SI zone), it was noted that, despite the differing R values for B6 and B8 at the beginning of curves, their resilience exhibited a more rapid increase compared to B5 and B10, primarily due to smaller bridge dimensions. The quickest restoration of bridges B6 and B8 (Preobradgensky bridge II, Zaporizha and Antoniv bridge I, Kherson) among all 18 assets could be explained by smaller T_{res} (due to small dimensions), which eliminated the comparatively higher T_{idl} in the Low SI zone. B15 exhibited the lowest resilience, driven by its high probability of failure and large area. Additionally, B15 was used as a reference bridge across all SI zones.

The impact of structural typology is most evident in bridges B4, B5, and B11, which demonstrate higher resilience values due to their greater resistance to blast loads compared to other assets in the medium, low, and high SI groups, respectively. In contrast, cable-stayed bridges B13 and B16, each with a single pylon and a significant risk of progressive failure in the event of local damage to the support, exhibit the lowest resilience values in their group. Additionally, the effects of long-term exploitation and higher degradation

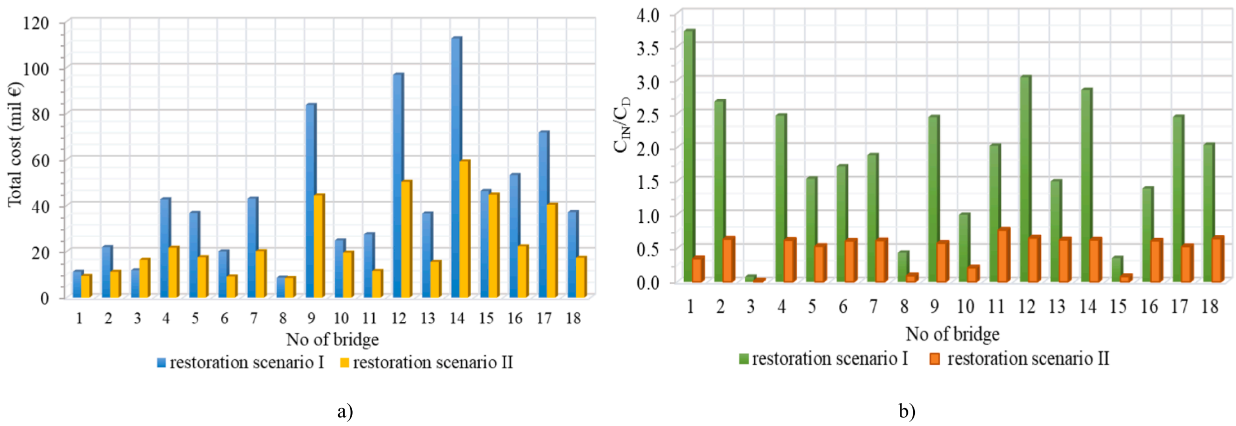


Fig. 6. Losses due to disrupted operation of bridges for restoration scenarios considering scenario I: complete disruption and scenario II with temporary works: (a) total costs C_{tot}, (b) ratio C_{IN}/C_D.

rates are reflected in the low initial R-values for B1, B2, and B3. Conversely, B18, built in 2010, shows a relatively high starting value on the R(t) graph.

In this case study, resilience was demonstrated to encompass both the robustness of the bridge and the speed of its restoration, integrated into a single value. Moreover, the impact of various risk mitigation strategies is directly reflected in the numerical parameters of resilience metrics. This was achieved by modifying fragility and restoration functions, as well as adjusting idle time, in response to infrastructural enhancements like the implementation of adaptation measures.

3.4. Economic impact assessment

Damage to bridges results in direct and indirect costs associated with economic and social impacts. Thus, direct losses were calculated as the finances, required for restoration of the asset (see Eq. A(6). The repair costs for 1 m^2 of the bridge of each typology were taken according to Ukrainian current practice as 2000 €/m^2 for truss bridges; RC girder, −1800 €/m^2; arch, −3000 €/m^2; steel girder, −3500 €/m^2 and cable-stayed, −4000 €/m^2. The ratio of repair costs for bridges in DS1-DS4 were 0.03, 0.08, 0.25 and 0.75, respectively (Argyroudis et al., 2020). Traffic deviations due to the closure of the bridge cause considerable indirect losses, which in this case study are calculated with the use of Eq. (A7-A8), where $C_{op,car}$ and $C_{op,truck}$ are 0.2 and 0.3 €/km, respectively and it is assumed that there is around 20 % of trucks in daily traffic (TR_D). Other values in the above equations were taken according to relevant prices in Ukraine: $C_{AW} = C_{ATC} = C_{goods} = 1$ €/h, $S_D = 50$ km/h, $S_0 = 90$ km/h, $S = 40$ km/h, $O_{car} = O_{truck} = 2$. To consider the cost increase, the inflation rate, reported by The IMF (2024) was used (which is 13 % in 2023 for Ukraine). Similarly, the discount rate was evaluated for 10 years, according to data provided by the reports of the Ministry of Finances of Ukraine (2022).

For this case study two scenarios were considered, representing two strategies for cost allocation:

(i) scenario I- in case of bridge failure, its operation is disrupted until the restoration works are completed and sufficient functionality level is reached as per the resilience curve;
(ii) scenario II- to avoid the complete disruption of the transport route, a temporary overpass is constructed, enabling the use of the route by cars but not by heavy vehicles.

For scenario II, the direct costs were increased by the additional cost of building the temporary overpass (4000 €/m), while the indirect costs were reduced. Approximate values of daily traffic on each of the assets were based on local traffic conditions and considered 5 % of the city's population. Hence, the daily traffic on the detour (ADT) was indicated: (i) for scenario I all the vehicles (cars and trucks) are using the detour and (ii) for scenario II,-cars can use the temporary overpass (remaining daily traffic on the bridge ADE) and the traffic on the detour consists only of heavy trucks (which are not allowed to use the temporary bridge). Calculated direct, indirect, and total costs for two scenarios are presented in Fig. 6 and Table 4. The ratio C_{IN}/C_D is the suggested representative measure for the analysis of the role of each asset in the transportation network.

Fig. 6 illustrates the role of direct and indirect costs in the total economic consequences of the bridge failure. These values are used for preliminary evaluation of the impact on sustainability in the economic sector (see Fig. 1) and cost-based resilience assessment (see Fig. 2). For almost all the assets of the case study, the total costs are lower in the second restoration scenario where a temporary overpass is constructed. However, it is important to take into account that this approach is associated with accelerated expense assignment, which in case of post-conflict recovery will be a significant burden on the state budget in the time of hostilities. Thus, for

Table 4
Direct and indirect economic losses for the bridges of the case study.

Bridge No	restoration scenario I				restoration scenario II			
	C_D (mil €)	C_{IN} (mil €)	C_{tot} (mil €)	$\frac{C_{IN}}{C_D}$	C_D (mil €)	C_{IN} (mil €)	C_{tot} (mil €)	$\frac{C_{IN}}{C_D}$
1	2.37	8.85	11.22	3.73	6.99	2.41	9.40	0.35
2	5.96	15.98	21.94	2.68	9.08	4.36	11.21	0.64
3	11.05	0.82	11.86	0.07	21.37	0.22	16.43	0.01
4	12.30	30.40	42.70	2.47	16.80	8.29	21.67	0.62
5	14.51	22.27	36.78	1.53	14.43	6.07	17.52	0.53
6	7.38	12.67	20.06	1.72	6.84	3.46	9.14	0.61
7	14.92	28.10	43.01	1.88	19.51	7.66	20.13	0.61
8	6.05	2.62	8.67	0.43	9.35	0.72	8.47	0.09
9	24.27	59.44	83.71	2.45	40.09	16.21	44.41	0.57
10	12.45	12.41	24.86	1.00	20.99	3.39	19.53	0.21
11	9.10	18.42	27.52	2.02	9.03	5.02	11.55	0.77
12	23.96	72.90	96.86	3.04	47.19	19.88	50.31	0.65
13	14.66	21.90	36.55	1.49	14.04	5.97	15.52	0.63
14	29.24	83.41	112.65	2.85	64.23	22.75	59.16	0.62
15	34.24	12.06	46.30	0.35	66.29	3.29	44.75	0.08
16	22.30	30.95	53.26	1.39	25.83	8.44	22.29	0.61
17	20.79	50.97	71.76	2.45	39.66	13.90	40.33	0.53
18	12.21	24.89	37.10	2.04	18.80	6.79	17.32	0.64

Table 5
Resilience and cost-based resilience metrics for the case study.

Bridge No	R	restoration scenario I				restoration scenario II			
		R_c ($\gamma = 0.05$)	R_c ($\gamma = 0.15$)	Impact ($\gamma = 0.05$)	Impact ($\gamma = 0.15$)	R_c ($\gamma = 0.05$)	R_c ($\gamma = 0.15$)	Impact* ($\gamma = 0.05$)	Impact* ($\gamma = 0.15$)
1	0.959	0.857	0.857	11 %	11 %	0.859	0.862	10 %	10 %
2	0.830	0.671	0.671	19 %	19 %	0.676	0.685	19 %	18 %
3	0.539	0.533	0.533	1 %	1 %	0.534	0.534	1 %	1 %
4	0.889	0.565	0.565	36 %	36 %	0.583	0.614	34 %	31 %
5	0.857	0.628	0.628	27 %	27 %	0.638	0.654	26 %	24 %
6	1.000	0.848	0.848	15 %	15 %	0.852	0.859	15 %	14 %
7	0.957	0.634	0.634	34 %	34 %	0.651	0.680	32 %	29 %
8	1.000	0.969	0.969	3 %	3 %	0.969	0.969	3 %	3 %
9	0.474	0.136	0.136	71 %	71 %	0.171	0.223	64 %	53 %
10	0.333	0.284	0.284	15 %	15 %	0.285	0.287	15 %	14 %
11	0.983	0.766	0.766	22 %	22 %	0.773	0.787	21 %	20 %
12	0.741	0.093	0.093	87 %	87 %	0.174	0.287	77 %	61 %
13	0.738	0.544	0.544	26 %	26 %	0.552	0.566	25 %	23 %
14	0.480	0.000	0.000	100 %	100 %	0.067	0.158	86 %	67 %
15	0.147	0.125	0.125	14 %	14 %	0.126	0.127	14 %	14 %
16	0.852	0.536	0.536	37 %	37 %	0.554	0.585	35 %	31 %
17	0.841	0.327	0.327	61 %	61 %	0.374	0.445	56 %	47 %
18	0.965	0.677	0.677	30 %	30 %	0.691	0.714	28 %	26 %

* Impact here refers to the relative change of R due to the introduction of the R_c index (Argyroudis et al (2020), Cimellaro (2016)).

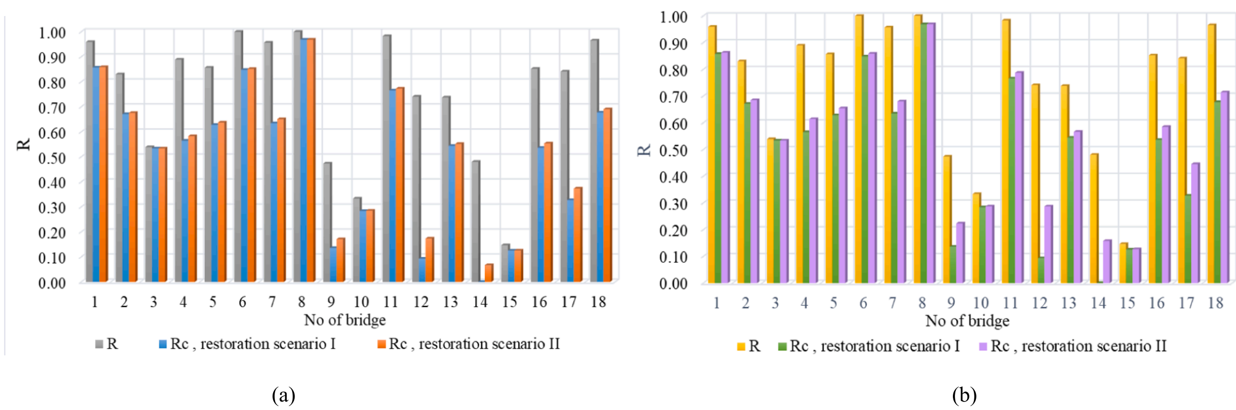


Fig. 7. Comparison of resilience (R) and cost-based resilience (R_c) values for two restoration scenarios and different levels of the indirect loss socio-economic impact: (a) $\gamma = 0.05$, (b) $\gamma = 0.15$.

instance, the highest economic effect of preservation of the transport route is noted for B14, B12, B9, a bit lower, – for B7, B16, B17, B18, and B4 (with lower total costs). It is notable, that all the bridges mentioned are located in regions with higher transport traffic: in the capital Kyiv and Dnipro (an important industrial and administrative centre). In contrast, although for B1, B2, B8, B10, and B15 the indirect losses in restoration scenario I are prevailing, the creation of an overpass has a small positive impact on cost savings. This can be explained by either lower traffic in cities with smaller populations (Mykolaiv- B10, Kherson-B15, B8) or smaller detour lengths (B1 and B2 in Kyiv). Additional attention should be paid to B3, for which scenario II is associated with higher total costs. The reason for this is the low traffic on this bridge as it is located in less populated areas (Kremenchuk). In summary, cost allocation decisions should prioritise the specific local needs of each asset.

3.5. Cost-based resilience

The approach for cost-based resilience calculation is described by Eq, (A4), where factor γ considers the socio-economic impact of indirect costs on network operations concerning direct losses. The particular value of γ should be estimated by stakeholders using expert judgment, taking into account the socio-economic impact of a bridge failure on transport infrastructure, and is influenced by factors such as the extent of damage, daily traffic, and access to critical facilities (Argyroudis et al., 2020). According to Cimellaro (2016) a reasonable range for γ is between 0.05 and 0.15. For the case study in this research study, results for both these values are presented (Argyroudis et al., 2020). For normalisation reasons, the targeted maximum restoration time was set within a range of 500 to 2000 days, and it was adjusted based on bridge size. Resilience loss, representing functionality loss, was quantitatively expressed using resilience indices that account for reductions due to specific damage levels. Cost-based resilience was evaluated across two restoration scenarios, considering both direct and indirect losses (see Table 5 and Fig. 7) and two values of γ. The variations in resilience values among the bridges can be attributed to differing probabilities of damage state (DS) occurrence.

Fig. 7 illustrates how the socio-economic consequences of a particular bridge failure in terms of direct and indirect losses could influence the resilience of the infrastructural system. In particular, it is noted that the restoration scenario I show a higher impact of indirect losses on the resilience of the portfolio of assets. This is reflected in the relative change of R due to the introduction of the R_c index (see columns Impact in Table 5), which indicates the significance of indirect costs to each asset's resilience; a lower ratio signifies that the asset is more critical in terms of indirect losses. In this context, R_C can serve as an additional decision-making tool, highlighting the consequences of indirect losses across different hazard scenarios and offering an objective method for stakeholders (Argyroudis et al., 2020; Cimellaro, 2016). Furthermore, in restoration scenario I, a strong correlation is observed between the higher impact of indirect losses and the associated economic effects (see Table 4). This is particularly evident for bridges B9, B12, B14, and B17, located in Dnipro. Although Kyiv, as the capital, experiences higher traffic volumes, the assets in this region (e.g., B1, B2, B7, B11, B13, B16, B18) are less vulnerable to the socio-economic impacts of route closures. This is due to the city's denser network of bridges and shorter detour distances. The varying impact of the γ factor on Kyiv's bridges can be attributed to differences in bridge dimensions and repair closure times; for example, B1 and B2, being smaller, have a lower impact. Similarly, the lowest socio-economic impact was observed for B3 in Kremenchuk, which, despite being an industrial centre, is less populated and has lower daily bridge traffic.

Addressing the socio-economic impacts of route closures due to bridge failures is essential for strengthening the overall resilience of transport infrastructure on a regional scale. By understanding and mitigating these effects, effective restoration planning can be achieved, enabling the prioritisation of proactive measures in infrastructure management and maintenance. This approach will not only enhance the general resilience of the transport network but also ensure the well-being of the communities it serves.

3.6. *Environmental and social impacts assessment*

The impacts of bridge damage or failure on sustainability in the social dimension were assessed with the use of the approach presented in section 2.3. Hence, among metrics of social consequences the following were used: possible number of casualties (injuries and fatalities-deaths), monetary losses due to casualties (amount of compensations) and period of the bridge closure (see Fig. 8 and Table 6). The potential number of casualties was calculated using Eq. (A10), where the number of people on the bridge at the time of failure was estimated based on daily traffic and the time spent on the bridge, which depends on its length and average traffic speed. To quantitatively assess the risks associated with bridge failure, the concept of the value of a statistical life was applied (Eq. A11-A13).

The average annual income of a person during labour time (salary) I_L and after retirement (pension) I_P were indicated from official sources (Ministry of Finances of Ukraine, 2024; Pension Fund of Ukraine, 2024). Values of average age (Age), retirement age (Age_{ret}) and average death age (Age_{death}) in Ukraine were taken from official open-access statistic databases (Official Digital Portal of Ukraine, 2024) (Archive of State Statistics Service of Ukraine, 2024; State Statistics Service of Ukraine, 2024)Mortality rate in Ukraine, 2024). Similarly, for the determination of the discount factor actual annual weighted average bank interest rate $\delta = 15\ \%$ was used (according to (Ministry of Finances of Ukraine, 2024)). The mortality rate M = 0.0159 in normal circumstances (before hostilities began in February 2022) was assessed with the use of statistical databases, mentioned above ((Archive of State Statistics Service of Ukraine, 2024; State Statistics Service of Ukraine, 2024) Mortality rate in Ukraine, 2024). Also, in Eq (A13) $\omega \in [0, 1]$ is a factor of local wealth circumstances (Kuchyňa, 2015). For this case study, average local wealth conditions were assumed, with ω set at 0.5.

To estimate the environmental impacts caused by required detours, sustainability metrics per vehicle unit distance were adopted from Padgett and Tapia (2013), with CO_{2_un} set at 0.25 kg/km and $E_{\_un}$ at 3.77 MJ/km. Additionally, the embodied CO_2 equivalent

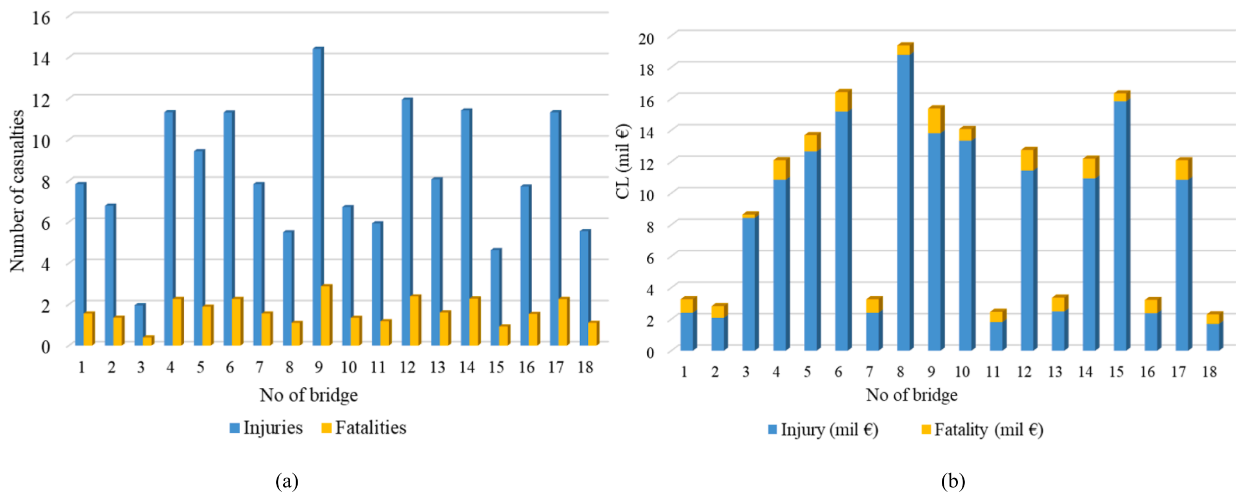


Fig. 8. Social consequences of possible failure/damage of each bridge: (a) possible number of casualties, (b) assumed monetary losses- CL (casualty losses).

Table 6
Bridge damage impact on sustainability – social and environmental dimensions.

No	Social consequences				Environmental consequences					
					restoration scenario I			restoration scenario II		
	N_I	N_D	CL (mil €)	DT (days)	CO_{2_D} (t CO_2 eq)	$E_{\_D}$ (MJ × 10^3)	CO_{2_R} (t CO_2 eq × 10^3)	CO_{2_D} (t CO_2 eq)	$E_{\_D}$ (MJ × 10^3)	CO_{2_R} (t CO_2 eq × 10^3)
1	8	2	3.27	199.31	6.83	101.13	2.80	1.37	20.23	19.24
2	7	1	2.83	383.16	21.27	314.92	6.05	4.25	62.98	17.02
3	2	0	8.65	370.91	189.42	2804.38	13.84	37.88	560.88	33.39
4	11	2	12.09	234.14	183.55	2717.39	11.84	36.71	543.48	30.55
5	9	2	13.69	244.68	214.19	3171.02	14.02	42.84	634.20	20.46
6	11	2	16.42	116.77	188.70	2793.61	6.82	37.74	558.72	9.44
7	8	2	3.27	848.21	108.53	1606.83	12.67	21.71	321.37	30.42
8	6	1	19.39	119.25	17.23	255.10	6.93	3.45	51.02	12.84
9	14	3	15.39	580.50	527.49	7809.41	32.78	105.50	1561.88	48.83
10	7	1	14.08	331.01	1881.65	27857.62	20.69	376.33	5571.52	29.32
11	6	1	2.47	506.88	34.02	503.73	7.25	6.80	100.75	15.10
12	12	2	12.75	822.50	599.14	8870.19	47.46	119.83	1774.04	64.46
13	8	2	3.37	673.92	23.13	342.41	12.39	4.63	68.48	21.78
14	11	2	12.19	1181.85	1106.56	16382.49	65.90	221.31	3276.50	85.81
15	5	1	16.34	908.21	991.70	14681.93	69.95	198.34	2936.39	85.66
16	8	2	3.22	1338.63	64.51	955.00	23.93	12.90	191.00	38.37
17	11	2	12.09	730.90	617.43	9140.92	39.86	123.49	1828.18	54.21
18	6	1	2.31	1215.36	45.85	678.84	16.72	9.17	135.77	28.98

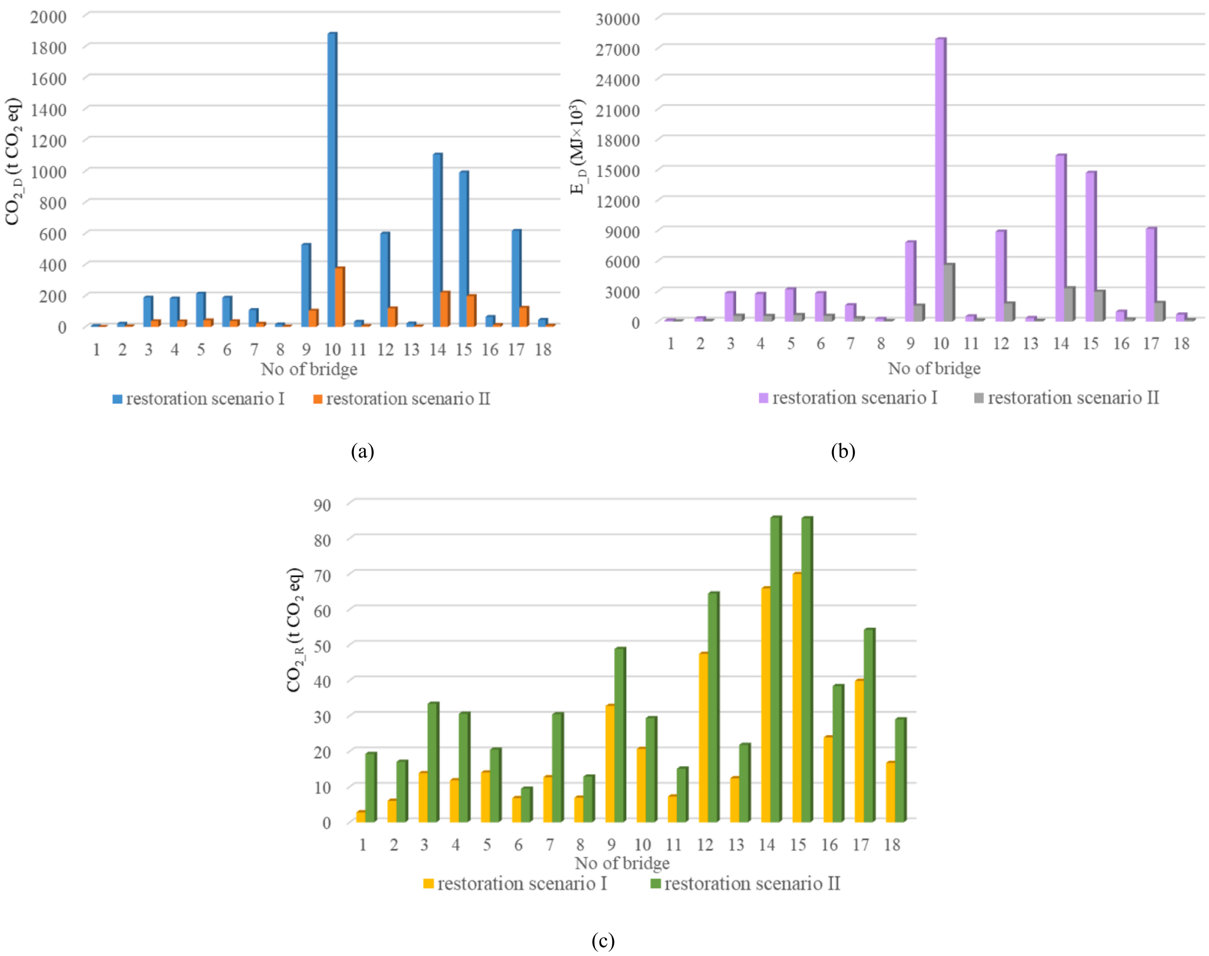


Fig. 9. Environmental impact of possible failure/damage of each bridge: (a),(b) due to required detour, (c) due to needed restoration works.

emissions from bridge repair work were calculated using Eq. (A17). The assumed unit area value, CO_{2_b}, was based on normalized values (Collings (2022)) and set at 2.3 and 2.4 tCO_2 eq./m^2 for concrete and steel, respectively, drawing from available datasets (Carbon, 2020; UK Department for Transport, 2013; International Union of Railways, 2016; Green Construction Board, 2013). It's important to note that these values are based on average energy production in Europe and may vary by region. The environmental impact of damage or failure for each asset is detailed in Fig. 9 and Table 6. Two restoration scenarios were considered for each asset, similar to the approach used for economic losses. In restoration scenario II, the additional embodied environmental impact from constructing a temporary 5 m-wide overpass was included, which increased embodied CO_2 eq. However, this scenario also assumes no detours for light cars were required due to the bridge disruption, thereby reducing indirect CO2 eq. and impacts related to energy consumption.

Fig. 8(a) demonstrates, that the social consequences in terms of casualty numbers are determined by the composition of different parameters: the daily traffic, estimated time on the bridge, and proximity of asset to the affected area (probability of high DS). Thus, a relatively lower number of fatalities could be expected due to the failure of B3 (Kremenchuk), B8 and B15 (Kherson), which are located in less populated cities. Despite the bridges B11, B18 are located in the most populated city (Kyiv), they are also associated with comparatively low risk for people, due to both lower estimated time, spent by an individual on a bridge) and longer distance from areas with hostilities and, thus, lower risk of accident. On the other hand, bridges, located in Dnipro are at higher risk of people injury (B4, B9, B12, B14, B17), due to their greater length and high daily traffic. In contrast, although both the population and length of bridges in Zaporizha are smaller (B6, B5), this estimated injury rate for assets in it is almost the same, which emphasizes the role of proximity to the conflict-prone region (the city is in Low SI zone). Similarly, for bridges in Mykolaiv (B10) and Kherson (B8, B15), which have the lowest daily traffic, location was the most critical factor for ensuring people's safety.

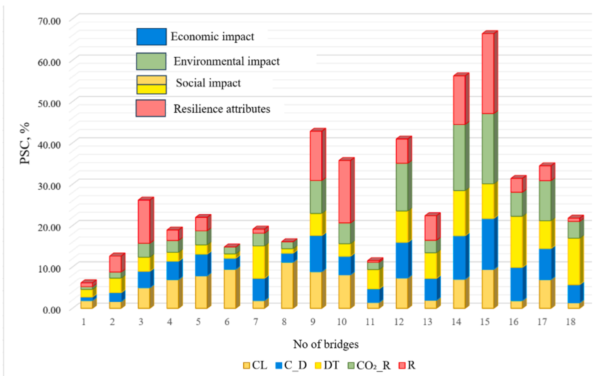
The possible injury rate evaluation in this study considered also its impact on individual health in future, taking into account the use of injury cost rate indices. Quantitative estimations (Table 6, Fig. 8 (b)) demonstrate, that monetary expression of social consequences is significantly dependent on bridge location. Thus, higher casualty losses (CL) were indicated for bridges in the Low SI zone: Kherson (B8, B15), Zaporizha (B5, B6), and Mykolaiv (B10), while other parameters are less impactful within this group. This pattern is further observed while increasing the distance from the area subjected to hostilities: slightly lower monetary losses were estimated for assets in Dnipro (B4, B9, B12, B14, B17) and Kremenchuk (B3) and the rapid decrease in CL range, −for High SI zone area (B1, B2, B7, B11, B13, B16, B18).

Although placing a monetary value on human life may appear controversial, it is a practical method for policymakers to prioritize and allocate resources in ways that maximize societal well-being. This measure should be viewed as a theoretical tool in economic analysis to assess the feasibility and societal impact of safety measures. Understanding this approach in cost-benefit analysis is crucial for shaping policies that aim to protect and enhance public health and safety. Downtime, as another metric of social consequences, is mostly influenced by the dimensions of bridges. In particular, bridges with the highest DT (Table 6) are B14, B16, and B18 in Kyiv and Dnipro and with the lowest,-B6, B8, B1, B4, B5 (in Zaporizha, Kherson, Kyiv), thus being independent on location and other factors.

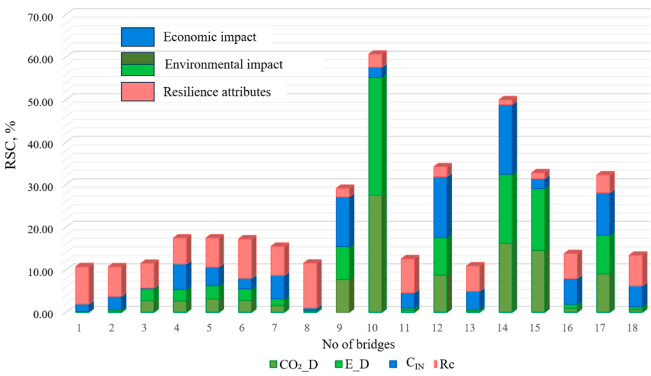
Table 6 and Fig. 9 demonstrate the environmental impact due to the required detour for 2 restoration scenarios (with and without arrangement of a temporary overpass). For the environmental consequences of the required detour, the detour length was the most significant factor. The highest values of both additional emissions and energy consumption due to detour are identified for B10 in Mykolaiv (with the longest detour length). Noteworthy, although the second longest detour is assumed for B3, CO_{2_D} and $E_{\_D}$ values were lower because of the small traffic in this area. On the other hand, bridges in Kyiv with the highest daily traffic are associated with small environmental metrics, due to better-developed transport infrastructure in the capital and shorter distances on the detour. For the remaining assets, the combination of factors has to be considered in each case: high environmental consequences for B14 and B17

Table 7
Results of normalised scoring technique, applied to the case study to facilitate decision-making and prioritisation.

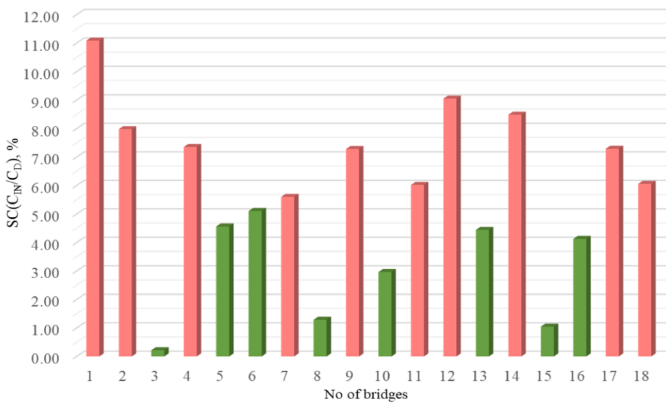
No	Scores for proactive measures (PSC), %						Scores for reactive measures (RSC), %						
	CL	C_D	DT	CO_{2_R}	ΔR	$\sum_{j=1}^{5} PSC_j$	C_{IN}/C_D	Scenario	CO_{2_D}	$E_{\_D}$	C_I	R_c	$\sum_{j=1}^{4} RSC_j$
1	1.88	0.85	1.84	0.68	0.93	6.18	11.09	II	0.10	0.10	1.74	8.80	10.74
2	1.63	2.15	3.55	1.47	3.85	12.64	7.98	II	0.31	0.31	3.14	6.95	10.72
3	4.98	3.98	3.43	3.36	10.44	26.19	0.22	I	2.78	2.78	0.16	5.80	11.52
4	6.96	4.43	2.17	2.87	2.52	18.95	7.35	II	2.69	2.69	5.97	6.12	17.47
5	7.88	5.22	2.26	3.40	3.25	22.01	4.57	I	3.14	3.14	4.37	6.83	17.48
6	9.45	2.66	1.08	1.65	0.00	14.84	5.11	I	2.77	2.77	2.49	9.22	17.25
7	1.88	5.37	7.85	3.08	0.98	19.16	5.60	II	1.59	1.59	5.52	6.80	15.51
8	11.16	2.18	1.10	1.68	0.00	16.12	1.29	I	0.25	0.25	0.52	10.53	11.55
9	8.85	8.74	5.37	7.96	11.92	42.84	7.29	II	7.73	7.73	11.68	2.02	29.16
10	8.10	4.48	3.06	5.02	15.10	35.76	2.97	I	27.59	27.59	2.44	3.09	60.70
11	1.42	3.28	4.69	1.76	0.39	11.53	6.02	II	0.50	0.50	3.62	7.98	12.59
12	7.33	8.62	7.61	11.52	5.87	40.97	9.05	II	8.78	8.78	14.32	2.36	34.24
13	1.94	5.28	6.24	3.01	5.94	22.40	4.44	I	0.34	0.34	4.30	5.92	10.90
14	7.02	10.53	10.94	16.00	11.77	56.24	8.49	II	16.22	16.22	16.38	1.15	49.98
15	9.40	12.33	8.40	16.98	19.33	66.44	1.05	I	14.54	14.54	2.37	1.36	32.81
16	1.85	8.03	12.39	5.81	3.34	31.42	4.13	I	0.95	0.95	6.08	5.83	13.80
17	6.96	7.49	6.76	9.68	3.60	34.48	7.29	II	9.05	9.05	10.01	4.19	32.30
18	1.33	4.40	11.25	4.06	0.79	21.82	6.06	II	0.67	0.67	4.89	7.18	13.41



(a)



(b)



(c)

Fig. 10. Normalised scores, for the bridges of the case study: (a)- scores for proactive measures (PSC), (b)- scores for reactive measures (RSC), (c)- normalised scores $SC(C_{IN}/C_D)$ as the criterion to choose the restoration scenario based on the ratio of indirect loses.

due to the integrated effect of above-average values of traffic and detour length; for B15, − long detour distance, although the traffic is low; for B12 and B9, −high traffic.

When analysing additional CO_2 eq. from repair work (Fig. 9, c), it is evident that the primary environmental impact stems from the construction materials used during retrofitting and the installation of a temporary overpass (in scenario II). Overall, the process of building a temporary overpass results in significantly higher greenhouse gas emissions, which far surpasses the differences in CO_{2_D} between the two scenarios. Comparative analysis between bridges within the case study shows, that the most critical consequences are expected for bridges B14, B15, B12 due to both, the use of concrete for the retrofitting process and larger sizes. It was observed that the location does not have a significant impact on this metric, however, the use of steel in the restoration process has a considerable positive effect in decreasing estimated GHG emissions (e.g. B1, B8, B7, B13).

3.7. Impact assessment for facilitating prioritisation based on global score

Impacts on resilience and sustainability, caused by potential bridge damage or failure were combined in a global score for each one of the assets. For this purpose, the approach, described in section 2.3 was applied to the bridges of the case study. Hence, factors, accounting for bridge resilience, environmental impacts, social considerations, and economic consequences in case of failure were integrated into a normalised score towards to facilitate comparisons and prioritisation. Results of normalised dimensionless scores according to the scheme in Fig. 3 and Eq. (1–2) are provided in Table 7 and Fig. 10 for both the proactive (PSC) and reactive prioritisation (RSC).

As shown in the direct losses impact assessment in Fig. 10(a), the dimensions of the assets and their location had the most significant influence on the prioritization of proactive rehabilitation measures. Hence, the highest PSC score was assigned to bridges B15, B14, B9, and B12, characterised by the greatest dimensions and those, located in low (Kherson-B15) and medium (B14, B9, B12-Dnipro) safety index zones. The necessity to take into account the proximity to the area with intense hostilities is also confirmed by relatively high PSC values (with a significant fraction of ΔR factor), obtained for B10, located in Mykolaiv (low SI zone), disrespectful to its small dimensions. On the other hand, for bridges, located more far from the demarcation line (e.g. B1, B2, B11 in Kyiv), overall proactive scores were low, due to the low possibility of direct attack on them. The typology and age had negligible impact on the resulting score.

Reactive restoration measures during post-conflict rehabilitation typically involve complex decisions on resource allocation and prioritization, which must consider the broader development of infrastructure across the country. An efficient approach to making decisions on rapid measures, such as the installation of temporary overpasses, could be guided by the extent of indirect losses resulting from bridge closures (see Fig. 10c). Normalised scores of indirect losses, facilitating the decision in reactive restoration strategy including indirect costs (C_{IN}), indirect CO_2 eq. (CO_{2_D}) and energy consumption ($E_{\_D}$) because of a required detour and cost-based resilience index R_c. Results (Fig. 10b) indicate that the highest priority during post-conflict rehabilitation should be given to assets in regions with less developed infrastructure, as they are crucial for communication between large areas. In particular, B10 (Mykolaiv) achieved the highest score due to the longest detour length. However, despite the significant detour length for B3 in Kremenchuk, the low daily traffic in this sparsely populated region mitigates the indirect losses from its closure, considerably lowering its overall score. In contrast, bridges located in Dnipro (B9, B12, B14, B17), a key industrial centre with high daily traffic, demonstrate a clear trend of increased indirect losses, highlighting their importance in the restoration process.

4. Limitations and future directions for research advancements

Due to its complexity, the proposed framework involves a number of assumptions and limitations, detailed in this section, alongside suggestions for future research. Due to limited data on conflict-induced damage mechanisms for various bridge types, fragility assessments relied on a thorough literature review and engineering judgement. A similar approach was used to estimate the duration of restoration works and idle times, as modelling specific local circumstances in conflict-affected regions remains challenging and requires further investigation. Sustainability metrics, in particular, the environmental ones, were assessed using impact per unit quantities from reliable datasets or, the averaged information from the literature. Despite these limitations and assumptions, the framework enables robust relative comparisons between different assets, which is critical for prioritisation. Future advancements can include more sophisticated tools to better predict damage and necessary repair measures, and quantify embodied and indirect environmental, societal and economic impacts.

The case study primarily utilised European-region databases, which may differ from the specific region studied. To overcome this possible limitation, more accurate information on traveling vehicle types can be used. This could improve the quantification of indirect environmental impacts. Overall, using geographically specific environmental data can refine embodied impact assessments. For repair impact assessment, expert judgment was applied. Future work, could integrate modelling tools for more accurate prediction of damage, required repair measures and time. Future research will also refine economic and societal metrics, incorporating detailed cost analysis of reconstruction efforts, factoring in regional variations in labour and material costs, and evaluating the socio-economic impacts of disrupted accessibility on local communities. Quantifying metrics such as job creation during reconstruction and the restoration of critical social functions would provide a more holistic evaluation of sustainability and resilience outcomes, ensuring that all selected metrics comprehensively address environmental, economic, and social dimensions.

While the primary focus of this study is on the strategic prioritization of infrastructure reconstruction, incorporating detailed structural analyses can significantly enhance the framework's technical robustness. For example, theoretical assessments of damage mechanisms, such as progressive collapse of bridges due to explosive impacts or degradation from sustained conflict-related stressors, could offer deeper insights into prioritisation criteria. Recent research on structural vulnerabilities and material performance under extreme conditions, such as (Hu, et al. (2024); Domaneschi et al. (2024a), Blikharskyy et al. (2021) could complement the proposed framework, particularly in evaluating repair versus replacement decisions. Future work could extend this approach by integrating detailed finite element analysis (FEA) or other structural analysis methods to quantify the extent of damage and its implications on resilience, and subsequently, sustainability metrics.

The proposed framework assumes a fixed duration of conflict and does not account for potential delays in reconstruction due to resource constraints or shifting priorities to other critical assets, such as hospitals or utility networks. These factors can significantly influence decision-making processes and resource allocation in real-world scenarios. Future framework enhancements will integrate dynamic variables to address these factors, improving its applicability across varying conflict scenarios.

Future research could validate the framework in other conflict-affected regions, broadening its applicability in diverse contexts. Although this study focuses on a case study in Ukraine, the framework could be adapted and applied to other conflict-affected regions, such as the Middle East, Africa, or Southeast Asia, where infrastructure faces similar challenges. Implementing and testing this framework in diverse social, economic, and environmental contexts would provide valuable insights into regional-specific adjustments, such as accounting for varying conflict dynamics, resource availability, emergency response protocols, or climate conditions. Broader application could offer tailored solutions for enhancing resilience and sustainability in increasing risk of emerging conflicts worldwide.

5. Conclusions

We introduced an integrated scoring-based framework for proactive and reactive infrastructure restoration, combining 10 resilience and sustainability metrics to guide post-disaster reconstruction and mitigate socioeconomic, environmental, and functional impacts. The focus is the recovery of regions affected by conflict, but the framewokr of htis paper can be adapted and used in any post-disasater situation. Our case study was focused on the restoration of bridges which are crucial to minimising impacts and ensuring safety, functionality, and sustainability in transportation networks. The analysis of the 18 largest bridges in Ukraine underscores the importance of multiple factors in prioritising both proactive and reactive measures in regions affected by conflict and human intervention. These factors include the strategic importance of each bridge, the availability of alternative routes, average daily traffic, bridge dimensions, significance for emergency evacuation, potential negative consequences for the social sector, and the environmental impact of a bridge failure, among others.

Integrating proactive measures to reduce vulnerabilities with reactive strategies for swift recovery enhances bridge resilience in conflict-prone regions. Research shows that indirect losses, such as disrupted supply chains and reduced economic activity, can be up to 10 times higher than direct losses incurred from bridge closures. The approach outlined in this study is adaptable to various hazards, using tailored vulnerability models to safeguard critical transportation links and support community well-being and mobility.

This paper highlights the paramount importance of resilience and sustainability impacts in guiding decisions for the reconstruction of bridge portfolios in conflict-affected regions, despite some methodological limitations. The unprecedented destruction of key transport assets during human-induced hazards underscores the urgency of adopting robust strategies centred on resilience and sustainability metrics for post-conflict restoration. The proposed framework provides a practical tool for prioritisation of resources and decision-making, essential for efficient reconstruction. This is the first of this kind of work, which introduces an integrated scoring-based prioritisation system to inform decisions for proactive and reactive restoration, mitigating social, economic, and environmental consequences of bridge failures. By addressing proximity factors, increased downtime, and normalised scoring for various restoration scenarios, this research contributes significantly to the field, particularly relevant to regions facing political and socio-economic instability.

Future work will focus on enhancing the framework's accuracy and applicability by refining metric calculations and integrating region-specific considerations. Incorporating localized data, such as vehicle types and traffic patterns, will improve the quantification of environmental impacts, while geographically tailored databases will enhance the assessment of embodied impacts. Additionally, predictive tools will complement expert judgment to provide more precise evaluations of damage, repair requirements, and timelines. Expanding the framework to include social and economic metrics, such as the costs of reconstruction, impacts on accessibility, and the extent of community disruption, will provide a more holistic approach. This human-centred perspective will account for proximity to settlements and critical infrastructure (e.g., airports, energy stations) to better address scenarios where failures result in severe community severance or disruption. These advancements will ensure more accurate, comprehensive, and actionable sustainability and resilience metrics for a wide range of contexts.

CRediT authorship contribution statement

Nadiia Kopiika: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Roberta Di Bari:** Writing – review & editing, Writing – original draft, Conceptualization. **Sotirios Argyroudis:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Jelena Ninic:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Stergios-Aristoteles Mitoulis:** Writing – review & editing, Funding acquisition, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex A. Equations to assess sustainability and resilience metrics (Section2)

Nomenclature.

F	Fragility	ADT	Average daily traffic on the detour	Age_{death}	Average death age
DS	Damage State	ADE	Remaining daily traffic on the bridge	ω	Factor of local wealth circumstances
IM	Intensity Measure	TR_D	Percent of trucks in the daily traffic	N_I	Number of injuries
Q	Functionality	C_{AW}	Average wage	N_D	Number of deaths
R	Resilience index	C_{ATC}	Total compensation	VSL	The Value of a Statistical Life
R_c	Cost-based resilience index	C_{goods}	Cost to transport goods in cargo (per hour)	VSL‘	The Value of a Statistical Life (considering mortality rate)
T_{idl}	Idle time	O_{car}	Daily traffic of cars	M	Mortality rate
T_{res}	Restoration time	O_{truck}	Daily traffic of trucks	I_L	Average annual income of person during labour time (salary)
C_D	Direct costs	S	Average velocity on the detour	I_P	Average annual income of person after retirement (pension),
C_{IN}	Indirect costs	S_D	Average velocity on the damaged bridge	N	Number of people on the bridge
C_{OP}	Operating cost of vehicles on a detour	So	Average velocity on the intact bridge	I_I	Injury index
C_{TL}	Cost due to vehicle time loss	r_f	Discount factor	I_D	Death index
LR	Loss ratio	r_p	Price increase rate	CO_{2_D}	Additional CO_2 eq. emissions due to detour
A	Area of the bridge	DI	Damage index	$E_{\_D}$	Additional embodied energy due to detour
DT	Downtime	IR	Injury rate	CO_{2_R}	Additional CO_2 eq. emissions due to repair works
D_l	Detour length	DR	Death rate	PSC_i,	Score for i-th asset in proactive prioritisation
S_{typ}	Typology index	Age	Average age		
S_{typ}	Typology index	Age_{ret}	Retirement age	RSC_i,	Score for i-th asset in reactive prioritisation

The following equations by Argyroudis et al. (2020) were used in the framework for the assessment of bridge resilience to ageing and conflict-induced hazards (see Section 2.2, Fig. 2).

Fragility (F) of the bridge, which is the measure of structural robustness, is defined as the probability of reaching or exceeding a certain Damage State (DS_i, i = [0…4])) for a given hazard Intensity Measure (IM):

$$F = P[ds > DS_i | IM], i = [0 \ldots 4] \tag{A1}$$

The speed of functionality recovery of the structure from different damaging scenarios (Q(t)) is defined via the resilience curve:

$$Q(t) = \sum_{i=0}^{4} Q[DS_i | t] P[DS_i | IM] \tag{A2}$$

where $Q[DS_i|t]$ is the functionality level of the asset after t time of restoration from each damage state.

The probabilities of occurrence of different damage states DS_i ($P[ds = DS_i|IM]$):

$$P[DS_i | IM] = \begin{cases} P[ds > DS_{i+1} | IM] - P[ds > DS_i | IM] \text{ if i } = 1 \ldots 3 \\ P[ds > DS_i | IM] \text{ if i } = 4 \end{cases} \tag{A3}$$

The resilience index defined from the area under functionality curve (*Q(t)*), normalized over a target time or maximum restoration time (t_r) (Argyroudis et al., 2020):

$$R = \frac{1}{t_r - t_0} \int_{t_0}^{t_r} Q(t) \tag{A4}$$

The variable t in function *Q(t)* is the sum of the idle time (T_{idl}) and restoration time ($T_{res,i}$); t_0 is the time point of the occurrence of an extreme event (e.g. the explosion). In this study, idle time is assumed regarding the location of the bridge (proximity to the region with ongoing hostilities).

The cost-based resilience index R_c takes into account indirect losses as resilience socio-economic metrics [6], [15]:

$$R_c = R\left(1 - \frac{C_D}{C_D + \gamma C_{IN}} \frac{C_{IN}}{C_{IN,\max}}\right) \tag{A5}$$

where C_D corresponds to direct costs for bridge restoration; $C_{IN} = C_{OP} + C_{TL}$ corresponds to indirect losses, as the sum of the operating cost of vehicles on a detour (C_{OP}) and the cost due to vehicle time loss (C_{TL}); $C_{IN,max}$ is the maximum indirect cost within the portfolio of bridges under study; γ is a factor that considers the socio-economic impact of indirect costs on network operations about direct losses (Argyroudis et al., 2020; Cimellaro, 2016).

Direct costs, required for bridge restoration (CD) are calculated by the following:

$$C_D = C \cdot W \cdot L \sum_{i=0}^{4} (P[ds = DS_i|IM] \cdot LR_i) \tag{A6}$$

In Eq. (A6) C is the assumed repair costs for 1 m^2 of bridge deck with similar typology, according to existing practices; W and L indicate its width and length, respectively; loss ratio LR_i refers to the proportion of losses incurred compared to the total potential losses under a given hazard scenario, defined in this research by composition of probability of occurrence of damage state and cost or damage ratio. These values are equal to 0.1, 0.25, 0.5 and 0.8 for DS1, DS2, DS3 and DS4, respectively.

The operating cost of vehicles on a detour (C_{OP}) and the cost due to vehicle time loss (C_{TL}) are calculated based on equations A(7) and A(8), respectively (Argyroudis et al., 2020; Decò et al., 2013; Dong and Frangopol, 2015):

$$C_{OP} = \sum_{i=1}^{4} \left\{ P[ds = DS_i|IM] \left(T_{idl,i} + \frac{T_{res,i}}{2}\right) \left[C_{OP,car}\left(1 - \frac{TR_D}{100}\right) + C_{OP,truck}\frac{TR_D}{100}\right] D_l ADT \right\} \tag{A7}$$

$$C_{TL} = \sum_{i=1}^{4} \left\{ \begin{array}{c} P[ds = DS_i|IM]\left(T_{idl,i} + \frac{T_{res,i}}{2}\right) \left[\begin{array}{c} C_{AW}O_{car}\left(1 - \frac{TR_D}{100}\right) \\ +(C_{ATC}O_{truck} + C_{goods})\frac{TR_D}{100} \end{array} \right] \frac{D_l}{S} ADT \\ +ADE\left(\frac{1}{S_D} - \frac{1}{S_0}\right) \end{array} \right\} \tag{A8}$$

where $C_{OP,car}$, $C_{OP,truck}$ are the average cost of cars and trucks operation on the route; D_l is the additional detour length; ADT and ADE indicate average daily traffic on the detour and remaining daily traffic on the bridge with limited operability. TR_D identifies a percent of trucks in the daily traffic; C_{AW}, C_{ATC} and C_{goods} are the average wages, total compensation, and the cost to transport goods in cargo (per hour). Daily number of cars and trucks on the route are denoted by O_{car} and O_{truck}, respectively; S, S_D and S_0 indicate the average velocity on the detour, on the damaged and intact bridge, respectively (Argyroudis et al., 2020). The idle and restoration time of a bridge due to a particular DS_i are denoted as $T_{idl,i}$, $T_{res,I}$, respectively. Losses due to disruption of the railway route (for railway bridges) are not considered in this framework. The dynamic nature of the economic sector was taken into account with price increase rate and discount rate for monetary losses (Di Bari et al., 2020a):

$$C_{i,j} = C_{i,j-1}\frac{1 - r_p}{(1 + r_f)^j}, \tag{A9}$$

where i denotes the type of costs considered (C_D, C_{OP}, C_{TL}); j- is a year belonging to the investigated period of bridge limited operation; $C_{i,j-1}$-costs in (j-1) year, r_f is the considered discount factor, r_p-price increase rate.

Approaches towards the evaluation of sustainability consequences of bridge damage or failure, available in international literature, were adopted to develop the resilience and sustainability-driven strategy for restoration and adaptation of bridge portfolios in conflict-induced regions (see Section 2.3, Fig. 2). The particular equations used are given below. A possible number of casualties (injuries N_I and deaths N_D) to assess the social dimension of the sustainability impacts (equation adopted from (Ellingwood and Wen, 2005; Padgett and Li, 2016):

$$N_I(N_D) = N \times I_I(I_D) = N\sum_{i=0}^{4} P[DS_i|IM] \times DI \times IR(DR), \tag{A10}$$

where N denotes the assumed number of people on the bridge at the time of the damage occurrence, I_I, I_D- injury and death indexes for each of DSs, respectively. Injury and death indexes are obtained from the multiplication of corresponding injury (IR) or death rate (DR) with damage index (DI) and probability of these DS. Damage index (DI) here is a metric used to quantify the extent of damage that a bridge has sustained and corresponds to each DS_i (in this application 4 DSs were considered, DS1 to DS4). Representative values for DI, DR, and IR were taken from the literature for each DS (Ellingwood and Wen, 2005; Padgett and Li, 2016, see Table A.1.).

Table A.1
Factors for assessing casualties considering different damage states (Ellingwood and Wen (2005)).

Damage state (DS)	DS1	DS2	DS3	DS4
Damage level characterisation	Minor structural damage and low probability of life-threatening injury	Medium level of damage	Significant damage level and significant risk of injury	Total failure and very high risk of life-threatening injury
Damage index (DI)	0	0.05	0.2	0.4
Injury rate (IR)	0	0	0.1	0.2
Death rate (DR)	0	0	0.01	0.04
Injury cost fraction	0.003	0.047	0.105	0.266

The Value of a Statistical Life (VSL) is the monetary dimension of losses due to possible casualties and is estimated with the use of the approach adopted from (Kartashova et al., 2019; Kuchyňa, 2015).

$$VSL = I_L \int_{Age}^{Age_{ret}} \exp(-r_f t)dt + I_P \int_{Age_{ret}}^{Age_{death}} \exp(-r_f t)dt, \tag{A11}$$

where I_L and I_P are the average annual income of a person during labour time (salary) and after retirement (pension), Age, Age_{ret} and Age_{death} correspond to the average age of a statistical person at the moment of accident, retirement age and average death age, respectively.

The discount factor r_f is determined by the actual annual weighted average bank interest rate δ:

$$r_f = \ln(1 + \delta) \qquad \text{A12)}$$

The dead-anyway effect is mentioned in several studies (Kartashova et al., 2019; Kuchyňa, 2015;Pratt and Zeckhauser, 1996) describing how VSL is influenced by current life longevity in a particular country/region. Thus, it can be assumed that the VSL will increase at a low level of survival probability (higher death rate):

$$VSL' = \frac{VSL}{p(1-\omega)} = \frac{VSL}{(1-M)(1-\omega)} \tag{A13}$$

where p denotes the probability of survival, M is the mortality rate and $\omega \in [0,1]$ is a factor of local wealth circumstances according to Kuchyňa (2015).

Losses due to injuries can be estimated by applying yielding coefficients to VSL (VSL'). Each injury level is assigned a value corresponding to an injury cost fraction (see Table A.1, Ellingwood and Wen, 2005;Padgett and Li, 2016; Office of the Secretary of Transportation, 2016). These costs should then be multiplied by the probable number of casualties (injuries N_I and deaths N_D) to evaluate the total casualty losses (CL).

Downtime (DT), the period during which the access to the structure is limited following a hazard occurrence, is estimated based on idle (T_{idl}) and restoration time (T_{res}) for various damage scenarios, considering the probability of their occurrence:

$$DT = \sum_{i=0}^{4} (T_{idl,i} + T_{res})[DS_i|t]P[DS_i|IM], \tag{A14}$$

Negative environmental consequences of the bridge closure and required detour could be estimated, based on unit metrics and the total amount of vehicles on the detour considering the total bridge downtime per damage state DT_i (Dehghani and Shafieezadeh, 2019):

$$CO_{2\_D} = \sum_{i=0}^{4} ADT \cdot DT_i \cdot D_l \cdot CO_2\_un \cdot P[DS_i|IM], \tag{A15}$$

$$E_{\_D} = \sum_{i=0}^{4} ADT \cdot DT_i \cdot D_l \cdot E_{\_un} \cdot P[DS_i|IM], \tag{A16}$$

where CO_{2_D} and $E_{\_D}$ are the indirect sustainability losses in the environmental dimension in terms of additional CO_2 eq. emissions and embodied energy due to bridge closure and required detour, respectively (see Table 1). CO_2_un and $E_{\_un}$ are corresponding losses per vehicle unit distance, DT_i- downtime per damage state i, D_l- detour length, and ADT – average daily traffic on the detour.

The assumed additional CO_2 eq. due to repair works on the damaged bridge are given by equation A17:

$$CO_{2\_R} = CO_{2\_b} \cdot LR \cdot A, \tag{A17}$$

where the CO_{2_b} is the assumed CO_2 eq. emissions, which are associated with the construction of 1 m^2 bridge of a particular type, A is the area of the bridge and LR is the loss ratio (Argyroudis, 2022). LR is a loss ratio, explained in Eq (A6).

Annex B. Details of the case study (Section 3)

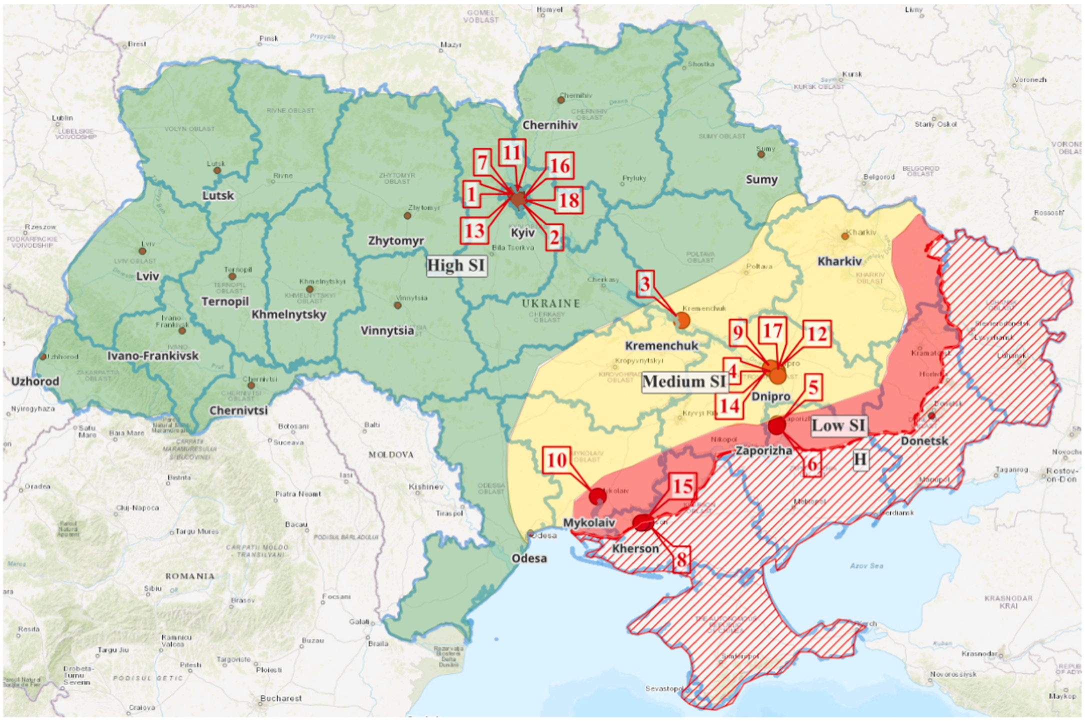
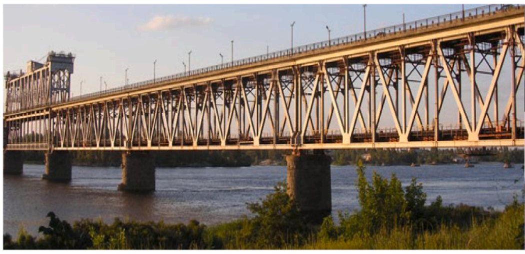


Fig. B.1. Location of bridges included in the case study. Red numbers correspond to 18 bridges: 1 to 18. Blue lines mark regional administrative borders. The Red dashed line indicates the border of the territory with ongoing hostilities (as for spring 2024, according to (DeepStateMap, 2024)). Coloured zones indicate: red hatch, marked as territories with hostilities (H); red, marked as a zone of Low Safety Index (SI); yellow, marked as a zone of Medium SI; green, marked as High SI

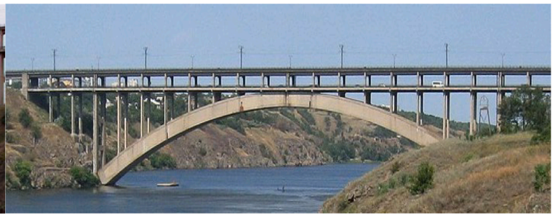

B1- Petrivsky bridge, Kyiv

B2 - Darnytsky bridge I, Kyiv




B3- Kryukiv bridge, Kremenchuk

B4- Marefa-Kherson Bridge, Dnipro

B5- Preobradgensky bridge I, Zaporizha

B6- Preobradgensky bridge II, Zaporizha

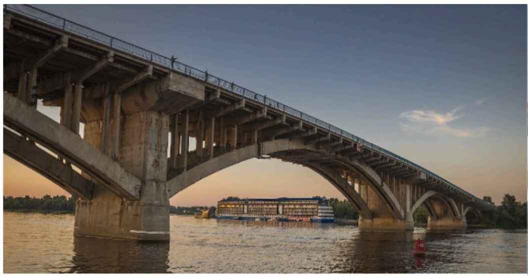

B7- Paton bridge, Kyiv

B8- Antoniv bridge I, Kherson


B9- Amur bridge, Dnipro

B10-Southern Bug bridge, Mykolaiv

Fig. B.2. Bridges used in the case study, having diverse materials and structural types, all crossing waterways.

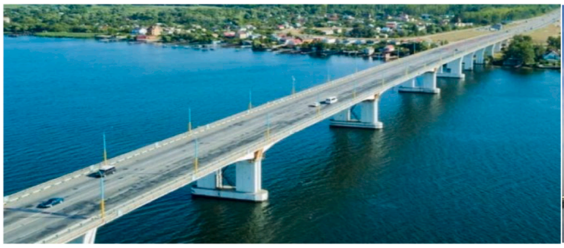


B11- Metro bridge, Kyiv

B12- Central bridge, Dnipro

B13- Northern bridge, Kyiv

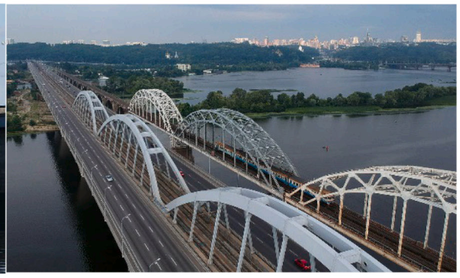
B14- Kaidatsky bridge, Dnipro



B15- Antoniv bridge II, Kherson

B16- Southern bridge, Kyiv

B17- Southern bridge, Dnipro



B18- Darnytsky bridge II, Kyiv

Fig. B.2. (*continued*).

Table B.1
Assumed probability of DS_i occurrence, considering the location of the asset (PI, SI).

No	$P[ds \geq DS_i \mid IM]$				$P[DS_i \mid IM]$				
	DS0	DS1	DS2	DS3	DS4	DS0	DS1	DS2	DS3
1	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
2	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
3	1	0.5	0.45	0.4	0.5	0.05	0.05	0.05	0.35
4	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
5	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
6	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
7	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
8	1	0.95	0.9	0.85	0.05	0.05	0.05	0.05	0.8
9	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
10	1	0.85	0.8	0.75	0.15	0.05	0.05	0.05	0.7
11	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
12	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
13	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
14	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
15	1	1	0.95	0.9	0	0.05	0.05	0.05	0.85
16	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1
17	1	0.75	0.7	0.65	0.25	0.05	0.05	0.05	0.6
18	1	0.25	0.2	0.15	0.75	0.05	0.05	0.05	0.1

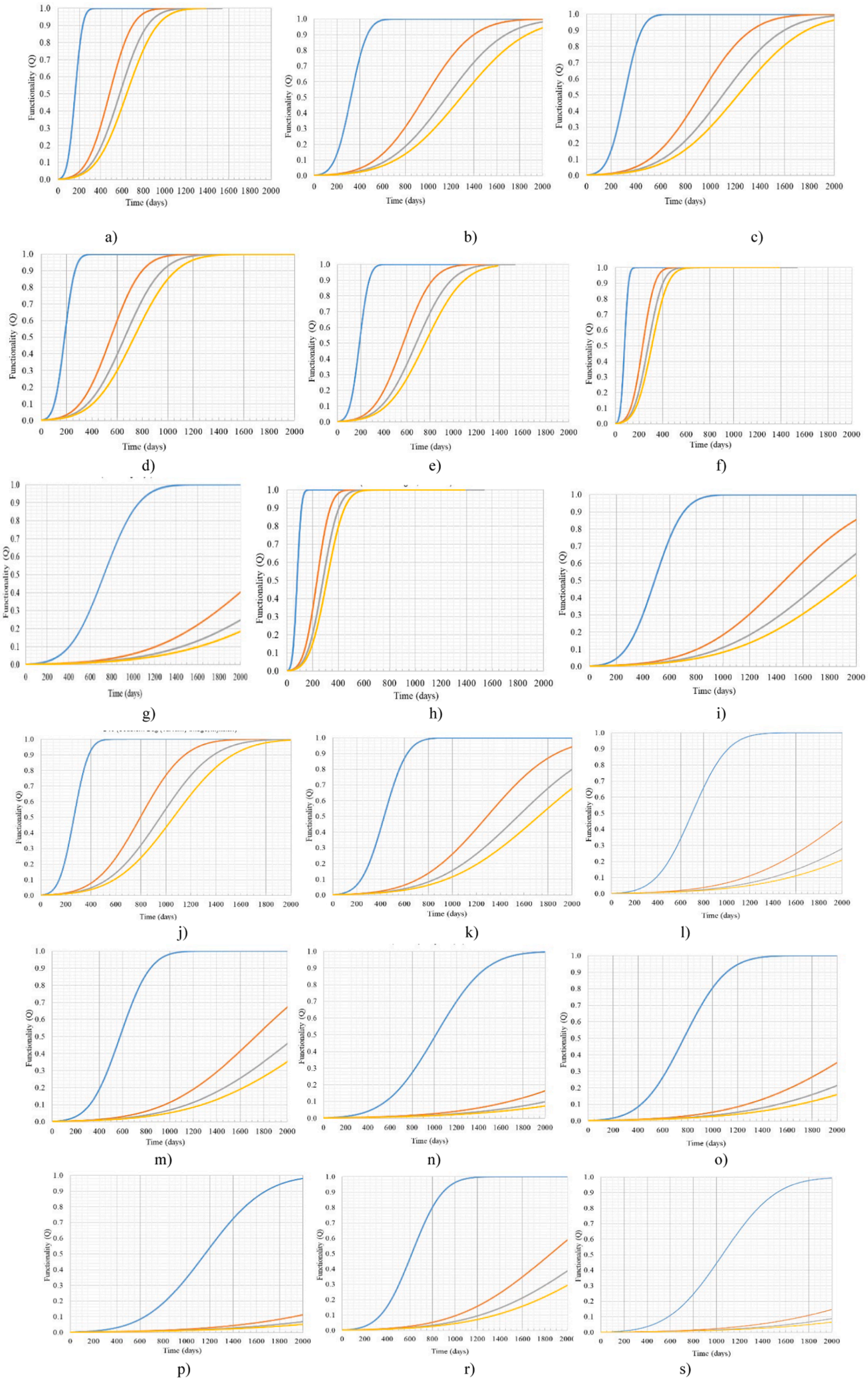


Fig. B.3. Restoration (functionality recovery) curves for bridges B1-B18 (a-s): −DS1, −DS2, −DS3, −DS4

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