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SUSTAINABILITY AND RESILIENCE-DRIVEN PRIORITIZATION FOR RESTORING CRITICAL INFRASTRUCTURE IN MULTI-HAZARD CONTEXTS: CONFLICT CASE

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Abstract. The accelerated deterioration and destruction of critical infrastructure due to conflicts, climate hazards, and human interventions leads to significant social, economic, and environmental impacts, particularly in multi-hazard environments. Effective recovery strategies must incorporate resilience and sustainability metrics to ensure infrastructure systems are adaptable and capable of addressing interconnected risks. However, there is a notable gap in knowledge, as comprehensive frameworks that incorporate these metrics in a unified and actionable way are currently lacking. This study introduces a framework for prioritizing the recovery of critical infrastructure, focusing on bridge portfolios in conflict-affected and multi-hazard regions. The framework uses a scoring system that integrates resilience and sustainability metrics, considering structural vulnerability, service criticality, environmental impact, and long-term functionality under uncertainty driven by proximity to conflict zones and the intensity of evolving hazards. Applied to a case study of major bridges in Ukraine, the methodology demonstrates how prioritization strategies can balance competing demands from local authorities, external donors, and global development goals. Results highlight the need to balance proactive measures like preventive strengthening with reactive post-disaster restoration to optimize recovery efforts in resource-constrained settings. The study also explores the challenges of aligning recovery priorities with sustainability targets in areas with limited resources and institutional capacity. This work provides decision-makers with a scalable tool for guiding strategic investment and aligns infrastructure recovery with global objectives like the SDGs, promoting long-term resilience in conflict- and disaster-affected regions.

1 INTRODUCTION

Proactive maintenance plays a crucial role in infrastructure management, ensuring the longevity and reliability of critical assets [1]. Bridges, as key components of transportation networks, are vital for economic stability, social well-being, and emergency response. However, they are increasingly exposed to diverse hazards, including natural disasters and human-induced threats [2]. The collapse of the Francis Scott Key Bridge in Baltimore highlights the severe economic consequences of infrastructure failures, with losses estimated at $15 million per day and insurance claims reaching $3 billion [3].

Conflict-prone regions present unique challenges for bridge resilience, as deliberate attacks, such as shelling and missile strikes, can cause immediate structural failures, prolonged disruptions, and significant economic and humanitarian consequences [4],[5]. Unlike natural hazards, conflict-related damage mechanisms involve direct blast impacts, progressive collapse due to secondary effects, and long-term degradation from neglected maintenance and overloading. Given these threats, traditional resilience frameworks fail to address the complexities of infrastructure recovery in such environments [6].

In addition to conflict-induced risks, ageing infrastructure and inadequate maintenance further exacerbate structural vulnerabilities. Corrosion, material fatigue, and prolonged exposure to extreme conditions increase the probability of failures, underscoring the need for proactive risk management and resilience planning [7]. Despite advancements in structural health monitoring and predictive modeling, there remains a gap in integrating conflict-aware resilience and sustainability metrics into infrastructure recovery strategies.

This paper builds upon recent research published in an extended journal article of the authors [8], further highlighting the discussion on resilience- and sustainability-driven infrastructure recovery in conflict-prone areas. By proposing a novel framework for prioritizing bridge restoration, this study synthesizes resilience and sustainability metrics to address the urgent need for informed decision-making [9]. Existing approaches primarily focus on climate-related hazards, neglecting the unique challenges posed by conflict-induced destruction. By incorporating a systematic prioritization methodology, this research aims to optimize resource allocation, enhance decision-making, and foster the sustainable recovery of transportation networks. The proposed approach is demonstrated through a case study in Ukraine, ensuring that bridge rehabilitation efforts not only restore functionality but also contribute to long-term resilience and sustainability in multi-hazard contexts.

2 METHODOLOGICAL APPROACH FOR RESILIENCE AND SUSTAINABILITY-DRIVEN CRITICAL INFRASTRUCTURE RESTORATION

2.1 Decision-making framework for bridge restoration

Restoring conflict-damaged infrastructure requires a comprehensive, evidence-based decision-making framework that balances sustainability and resilience to ensure long-term functionality. Although these two concepts are distinct, they intersect in bridge system evaluations. The proposed framework (Figure 1) prioritizes restoration efforts through a structured scoring system that integrates key sustainability and resilience parameters. The framework first determines whether a region has experienced conflict-induced destruction, including the extent of damage. If a region is at risk but remains unaffected, proactive strategies are implemented to enhance resilience, including structural strengthening, monitoring systems, and protective measures. If damage has already occurred, a reactive prioritization approach is applied to restore critical infrastructure efficiently, minimizing direct and indirect socio-economic losses.

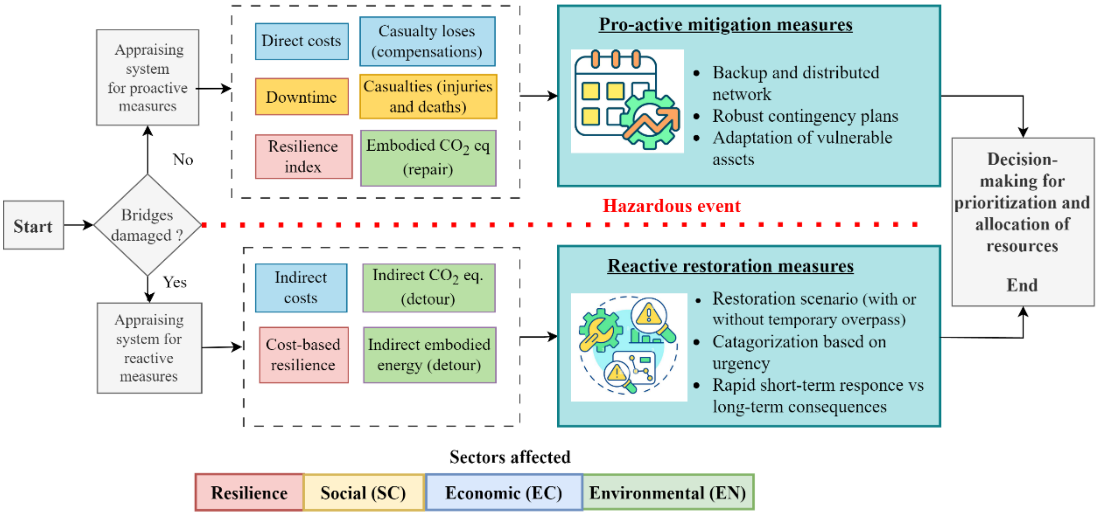

Figure 1: The general framework for sustainability- and resilience-driven decision-making for critical infrastructure restoration in hazardous areas. The three dimensions of sustainability impact are indicated with colours: **blue**-economic, **yellow**-social, **green**-environmental. Resilience components are shown in **red**.

This decision-making process is facilitated by the appraisal system focused on optimizing resource allocation by integrating sustainability (economic, social, green) and resilience parameters. Proactive adaptation strategies aim to reduce direct losses, such as immediate repair costs and environmental impacts, while reactive strategies mitigate indirect losses resulting from prolonged disruptions. This systematic approach allows decision-makers to prioritize the restoration of bridges whose failure would have the most severe economic (see ***blue*** colour in Figure 1), social (***yellow*** colour), environmental (***green*** colour), and resilience-related (***red*** colour) consequences.

2.2 Resilience parameters in restoration of conflict-affected critical infrastructure

Resilience assessment of critical infrastructure has traditionally focused on natural hazards [10],[11]. Given the time-dependent nature of recovery, resilience curves are usually used to model the functional restoration trajectory of a bridge under different intervention scenarios. These curves illustrate how quickly a structure regains its operational capacity and help in comparing the effectiveness of various repair strategies. They also enable decision-makers to anticipate the long-term implications of delayed restoration efforts, ensuring that limited resources are allocated where they are most needed.

However, conflict-related threats introduce additional complexities, requiring a tailored resilience evaluation framework. Resilience metrics provide a structured approach for assessing a bridge's capacity to withstand and recover from damage caused by adverse events, including armed conflict [11],[12]. These metrics encompass four key dimensions: robustness, redundancy, resourcefulness, and rapidity. **Robustness** evaluates structural integrity under extreme loading conditions, while **redundancy** ensures that alternative routes or systems can mitigate the loss of functionality [13]. **Resourcefulness** reflects the ability to efficiently mobilize resources for emergency response, and **rapidity** measures the speed at which a bridge can be restored to operational status (see Figure 2).

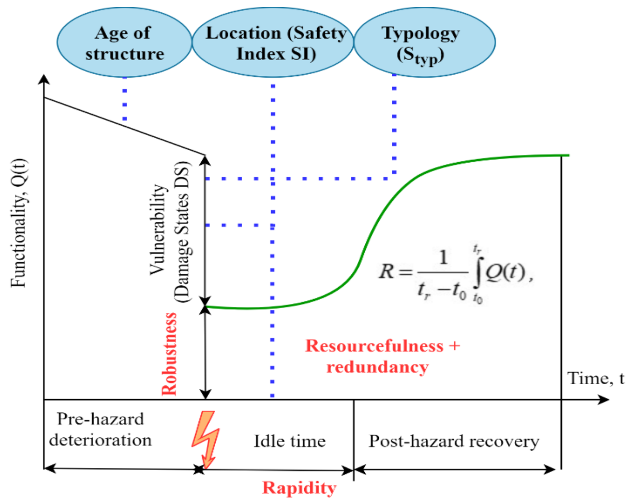

Figure 2: The general scheme for resilience metrics and components (shown in **red**).

In conflict-affected regions, infrastructure vulnerability is heightened, and disruptions to transport routes can have cascading socio-economic consequences, affecting supply chains, humanitarian aid, and evacuation efforts. Therefore, resilience assessments must account for both direct functionality losses and indirect impacts, such as prolonged detours and economic disruptions. This study extends traditional resilience evaluation methods by incorporating parameters specifically relevant to conflict-related threats:

- **Location-The Safety Index (SI)** quantifies the probability of a close-range detonation, taking into account stand-off distance from the zone of intense hostilities (accounting also for longer idle times due to limited access and possibility to begin recovery).
- **Typology- The Typology Index (S_{typ})** classifies bridge vulnerability based on structural characteristics, including material properties, redundancy, and age.
- Bridge **Damage States** (DS0–DS4) integrate factors such as deterioration effects and proximity to conflict zones.

To provide a comprehensive resilience assessment, the Resilience Index (R) measures a bridge's ability to maintain functionality and recover post-damage, while the Cost-Based Resilience Index (R_C) accounts for direct and indirect socio-economic losses, ensuring a holistic evaluation [12],[14]. For a more detailed presentation of the equations and methodological approach, readers are encouraged to refer to the recent research paper [8].

Resilience, therefore, involves not only reducing the likelihood of failure but also minimizing the consequences of such failures and ensuring a rapid recovery process. By integrating these resilience-specific parameters into the prioritization framework, this study advances decision-making methodologies for post-conflict bridge restoration, emphasizing both immediate recovery and long-term functionality.

2.3 Sustainability Parameters in Bridge Recovery

The impact of bridge damage on sustainability is assessed through an integrated framework considering economic (EC), environmental (EN), and societal (SC) dimensions (as illustrated by Figure 1). Structural failures compromise not only the functionality of the infrastructure but also the broader goals of sustainable development. Economic metrics include Direct Costs (C_D),—expenses related to material, labor, and logistics for repair—and Indirect Costs (C_{IN}), which represent broader economic losses such as detour-related travel delays, increased fuel use, and disruptions to supply chains. These monetary losses, while commonly used in infrastructure prioritization, fail to capture the full extent of social and environmental implications.

Downtime (DT), reflecting the period during which a bridge is inaccessible, has a dual role: it directly impacts socioeconomic activity and serves as a measure for estimating detour-related environmental consequences. Additional energy consumption (E_D) and greenhouse gas emissions (CO_2_D) associated with detours are captured alongside embodied emissions (CO_2_R) from repair processes. These environmental metrics are quantified following ISO 14040, 14044, and 15686 standards and rely on both traffic data and expert-based assumptions due to uncertainty in damage extent.

The societal consequences are further addressed through Casualty Losses (CL), expressed in monetary terms using the Value of a Statistical Life (VSL) approach [15]. While inherently controversial, this method—grounded in human capital theory—enables policy-relevant estimations of losses associated with injuries and fatalities (N_I, N_D), which are calculated using probabilistic damage-state models, based on both population and traffic activity data for the particular region. As supported by [16],[17], this approach allows for a preliminary yet consistent estimation of social impacts, critical in the context of resilience planning.

This multi-metric, holistic approach—detailed with specific equations in [8]—enables a more comprehensive assessment of sustainability, supporting the integration of economic, environmental, and societal metrics into the planning of critical infrastructure adaptation and restoration (see Figure 3). By moving beyond traditional cost-based prioritization, this methodology captures often-overlooked consequences such as human casualties, elevated emissions, and prolonged service disruptions—factors that are increasingly central to future-proof and resilience-driven infrastructure strategies.

2.4 Integrating Resilience and Sustainability into Prioritization

Effective planning for mitigation and restoration in areas affected by conflict requires a comprehensive evaluation of factors tied to sustainability and resilience. This section builds on the genera framework of Figure 1 and introduces an integrated scoring system, designed to support prioritization based on these dimensions, ensuring that investments in infrastructure adaptation are both strategic and impactful. A structured scoring system (see Figure 3) is developed to assess critical assets by examining their environmental footprint, social implications, economic effects, and their robustness and recoverability during disruptive events. The framework enables decision-makers to comprehensively assess the cumulative impact of various risks and plan accordingly. It supports:

(i) prioritization of **proactive measures**—preemptive actions to reduce vulnerability and mitigate damage;

(ii) informed implementation of **reactive measures**—post-damage responses such as rapid repairs and temporary overpasses to restore functionality.

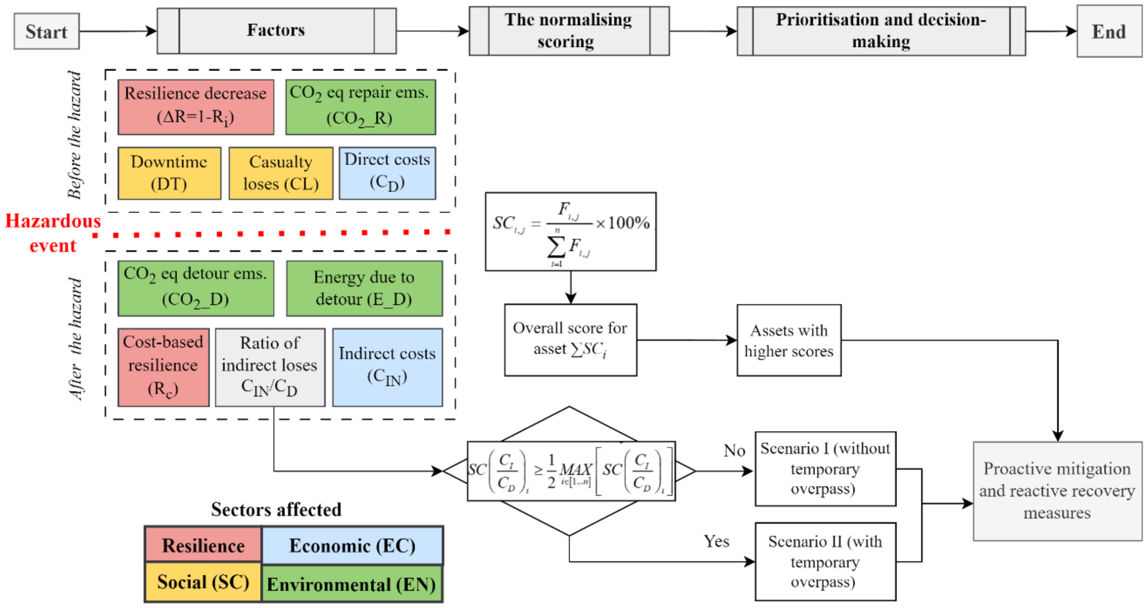

Figure 3: The scoring framework to support decision-making in prioritization of proactive and reactive recovery measures.

In this context, all consequences of bridge failure are classified as either **time-independent** (inevitable or default losses) or **time-dependent** indirect losses, which escalate with prolonged disruption. Proactive strategies focus on minimizing direct impacts—repair costs (C_D), casualty losses (CL), downtime (DT), and embodied CO_2 emissions (CO_2_R)—by strengthening high-priority assets before failure. Conversely, reactive strategies address indirect impacts such as economic losses (C_{IN}) and detour-related emissions (CO_2_D) and energy use (E_D), which typically far exceed initial repair costs. A cost-based resilience index (R_c) is employed to reflect the socio-economic implications of service disruption. For post-conflict recovery, assets generating high time-dependent losses are prioritized for restoration to optimize resource allocation and minimize extended consequences.

To operationalize this framework, a scoring system is applied, integrating normalized values of sustainability and resilience metrics. Each score is transformed into a dimensionless value using established normalization techniques [18] enabling direct comparison across different factors. For a given factor [$F_1 \ldots F_n$] across assets [1…n], the normalized score SC for the i-th asset is calculated as:

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

where j corresponds to the number of factors.

This allows for weighted aggregation of normalized scores, producing an overall Proactive Score (PSC_i) for proactive planning and a Reactive Score (RSC_i) for post-damage recovery strategy, as illustrated in Figure 3.

In developing recovery strategies, the C_{IN}/C_D ratio serves as a key decision-making criterion to evaluate the justification for deploying a temporary overpass. When the normalized score for this ratio exceeds 50% of the maximum score within the asset portfolio, it reveals substantial indirect losses resulting from the bridge closure. In such cases, implementing a temporary solution is considered both necessary and cost-effective to mitigate prolonged disruptions. The decision criterion is given by:

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

By combining forward-looking mitigation with responsive restoration strategies, this framework enhances the robustness of bridge infrastructure in regions exposed to conflict. Preventive actions help reduce vulnerabilities in advance, while reactive responses facilitate swift recovery when damage occurs. Furthermore, the proposed methodology is flexible and can be adapted to address a range of hazards beyond conflict scenarios, provided that appropriate vulnerability models are incorporated. Altogether, this approach supports the continuity of vital transportation infrastructure and helps safeguard the communities that depend on it.

3 APPLICATION TO THE CONFLICT CASE AND RESULTS

3.1 The Case Study- Bridges in Ukraine

Ukraine's bridge stock is in a state of widespread deterioration—around 81% were constructed before 1981, and many have exceeded their service life [19]. Environmental stressors such as corrosion, fatigue, and increasing traffic loads have further worsened their condition. Compounding this, outdated design standards leave most bridges incompatible with current demands. Recent estimates suggest only about 14% are in satisfactory condition, with the rest functioning under reduced safety margins [20]. The ongoing conflict has further accelerated the degradation of critical infrastructure. Bridges, as essential transport corridors, have become key targets in combat zones. In regions such as Kherson, Zaporizhzhia, and Mykolaiv, these structures are not only logistical lifelines but also critical for evacuation and humanitarian access. Their loss can severely disrupt mobility, isolate communities, and impede both military and civil operations [21].

To demonstrate the applicability of the proposed sustainability- and resilience-based prioritisation framework, we applied it to a portfolio of 18 major bridges across Ukraine. These bridges, among the largest in the country, were selected due to their strategic, economic, and social importance in ensuring national and regional connectivity.

A key element of the analysis was the proximity-based Safety Index (SI), representing the bridge's distance to conflict zones, normalized within the portfolio. Based on this, bridges were grouped into three zones: Low SI (0.01–0.3) near hostilities, Medium SI (0.3–0.7) at intermediate distances, and High SI (0.7–1) in safer areas. For instance, Kyiv's bridges scored high SI values (0.9–1), while Mykolaiv and Kherson bridges fell into the Low SI range. The Antoniv Bridge II (B15) in Kherson—destroyed during the conflict—was used as a reference point for location-based vulnerability. While Figure 4 illustrates the location of bridges, more details about the case study, including exact coordinates, structural features, dimensions, year of construction are available in [8].

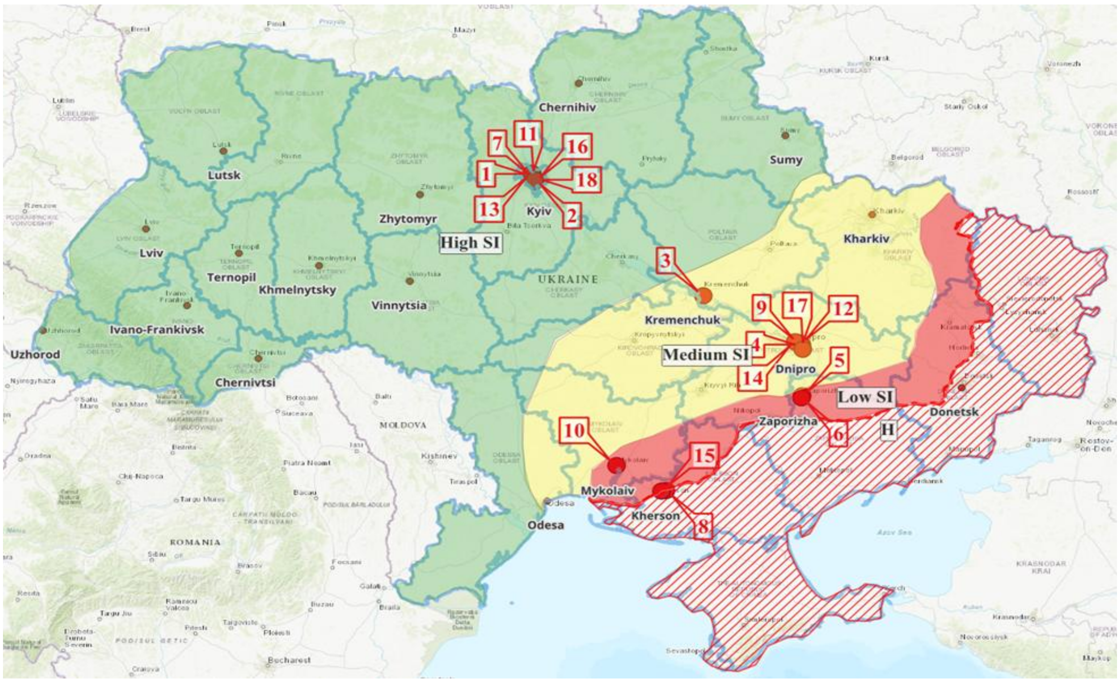

Figure 4: Location of 18 bridges included in the case study, with red markers denoting the assets, administrative borders in blue, and coloured zones indicating proximity-based SI classifications: red hatch for active hostilities (as for spring, 2024), red for Low SI, yellow for Medium SI, and green for High SI.

Each bridge was classified using a coding scheme reflecting its structural type (truss, arch, girder, cable-stayed), span configuration (single/multi-span or pylon), and material (steel, reinforced concrete, or hybrid). The analysis, hence, considered typological vulnerability through a structural index (S_{typ}) indicating sensitivity to blast damage, and age-related deterioration using a factor (S_{age}) that adjusts performance based on decade of construction. Bridges built before 2000 were penalized by 2.5–10% reductions in capacity per decade, depending on the damage state. If prior restoration was identified, it was factored in by adjusting the asset's effective age. Population data from nearby cities were used to estimate daily bridge traffic, providing insight into the potential disruption to local social life in the event of closure.

3.2 Assessment of Resilience, Economic, Environmental, and Social Factors

This section provides a summary of the resilience, socio-economic, and environmental assessments of individual factors, which are subsequently integrated into a comprehensive scoring and prioritization of assets (more details can be found in [8]). Resilience metrics for bridges in the case study were estimated based on assumed restoration times. Since detailed repair strategies for explosion and blast-induced damage are scarce in international literature, restoration time was derived from previous studies [10],[11],[22]. For complete destruction (DS4) restoration was assumed to take 90 days per 1000 m² Reduction coefficients were applied to represent partial damage levels: 75% for DS1, 25% for DS2, and 10% for DS3. Idle times were also considered, especially in regions with ongoing hostilities, affecting restoration timelines. These idle times ranged from 15 days for DS1 to 60 days for DS4. To address uncertainty in recovery times, a probabilistic model using Monte Carlo simulations was applied, with restoration time following a normal distribution. The resilience curves showed varying recovery patterns depending on asset size and location, with smaller bridges in higher-risk zones (Low SI) exhibiting faster recovery rates. Larger bridges, like B15, had lower resilience due to higher failure probabilities and larger areas. The study also revealed that structural typology played a significant role in resilience, with cable-stayed bridges (e.g., B13, B16) exhibiting lower resilience, while truss and arch bridges showed higher resilience. The presence of long-term degradation effects, such as corrosion, also influenced resilience, with newer bridges like B18 performing better.

Damage to bridges leads to both direct and indirect costs. Direct costs were calculated based on repair costs per square meter for different bridge types, with costs ranging from €2000/m² for truss bridges to €4000/m² for cable-stayed bridges. Indirect costs due to traffic deviations were calculated, considering both cars and trucks. Two scenarios were considered for cost allocation: (i) restoration delays until full functionality is restored and (ii) the construction of a temporary overpass to maintain some traffic flow. The economic analysis found that constructing a temporary overpass generally reduced total costs, though it accelerated expenses, which could burden the state budget during conflict. Bridges in high-traffic areas, such as Kyiv and Dnipro, showed the greatest cost savings when using temporary overpasses. For low-traffic areas (e.g., Kremenchuk, Mykolaiv), the creation of an overpass had a smaller impact.

Cost-based resilience (R_c) was calculated to account for both direct and indirect losses, as well as the socio-economic impact of bridge failure.

Social consequences of bridge failure were assessed using metrics such as potential casualties, compensation costs, and downtime (see Figure 3). Casualties were estimated based on daily traffic and bridge location, with bridges in areas near hostilities (Low SI) posing higher risks. The highest casualty rates were observed for bridges in Dnipro (B4, B9, B12, B14) and low-traffic areas such as Kherson (B8, B15)[8]. Monetary losses due to casualties varied significantly by location, with higher losses in conflict-prone areas. Environmental impacts were also considered, with detour-related CO_2 equivalent emissions and repair-related embodied CO_2 equivalent calculated[7]. Scenario, which included constructing a temporary overpass, reduced detour emissions but added to the environmental cost of construction.

3.3 Impact Assessment for Prioritization Based on Global Score

This section combines resilience, sustainability, environmental, social, and economic impacts of potential bridge failures into a global score for asset prioritization. The approach described in Section 2.4 was applied to the case study bridges, normalizing these factors into a score to aid comparison and decision-making. Normalized scores for proactive (PSC) and reactive (RSC) prioritization are shown in Figure 5. For proactive measures, asset size and location were key factors, with bridges in low (Kherson-B15) and medium (Dnipro-B14, B9, B12) safety zones receiving the highest PSC scores. Proximity to conflict zones, such as B10 (Mykolaiv), also influenced the score, despite its smaller size. Bridges in safer areas, like Kyiv (B1, B2, B11), had lower scores due to the reduced risk of attack. Bridge typology and age had minimal influence on the scores.

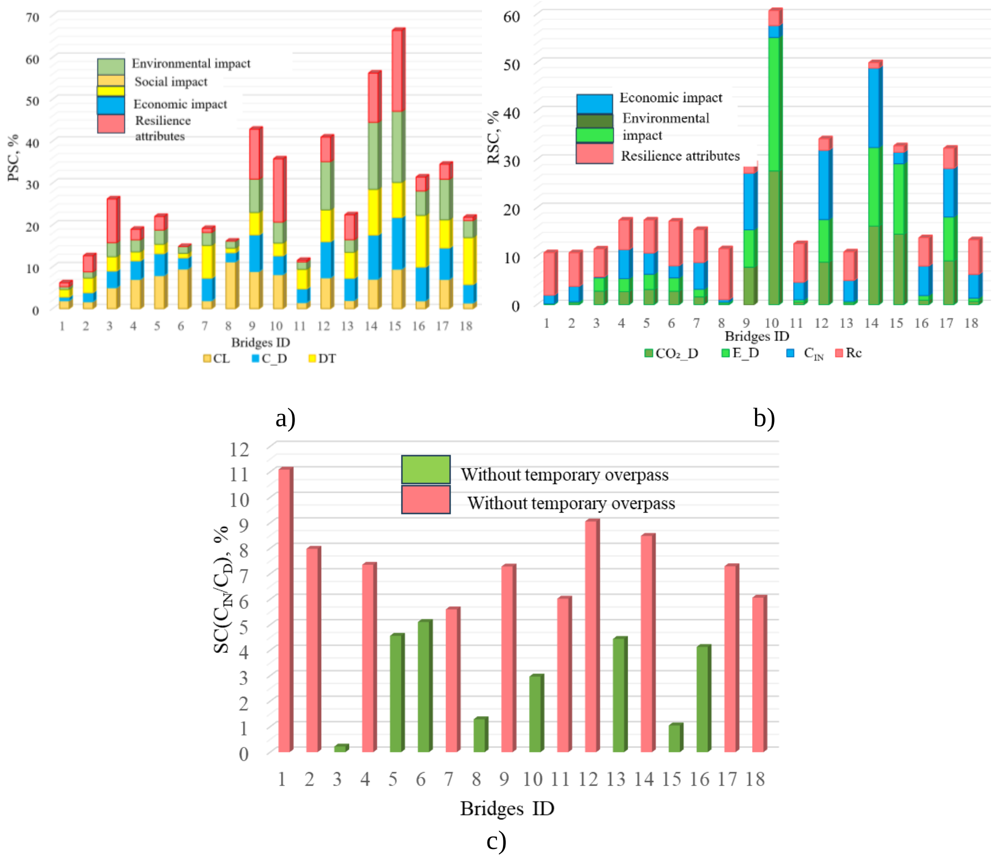

Figure 5: Global scores for the bridges of the case study: (a)- for proactive measures (PSC), (b)- for reactive measures (RSC), (c)-normalised scores SC(C_{IN}/C_D) as the criterion to choose the restoration scenario [8].

For reactive restoration, decisions on resource allocation focus on minimizing indirect losses due to bridge closures, such as detour length and infrastructure impact. B10 (Mykolaiv) had the highest score for indirect losses due to long detour lengths. Conversely, B3 in Kremenchuk had a lower score due to lower traffic volumes despite its long detour. Bridges in Dnipro (B9, B12, B14, B17), with high traffic, showed higher indirect losses, emphasizing their priority in post-conflict rehabilitation.

4 CONCLUSIONS

Bridges are crucial to transportation networks, and their failure can lead to significant direct and indirect consequences, impacting human lives, economies, and the environment. Regular proactive maintenance and efficient reactive protocols are essential for minimizing these risks and ensuring infrastructure reliability. This study emphasizes the importance of assessing bridge resilience to extreme hazards, particularly in post-conflict scenarios, to minimize socioeconomic impacts and support infrastructure sustainability. The proposed framework offers a practical tool for prioritizing resources and decision-making in the restoration of bridges, with a focus on resilience and sustainability. It integrates both proactive and reactive measures, factoring in key elements like proximity to conflict zones, bridge dimensions, and social and environmental impacts, to optimize decision-making. The case study of Ukraine demonstrates the framework's effectiveness in real-world conditions, highlighting its value in mitigating human-induced hazards and improving infrastructure recovery efforts. By combining proactive strategies to reduce vulnerabilities and reactive measures for swift recovery, this approach contributes significantly to enhancing bridge resilience in conflict-prone regions. It can also be adapted to address various other threats, ensuring the protection of vital infrastructure and the mobility of affected communities.

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