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Conflict-resilience framework for critical infrastructure peacebuilding

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ABSTRACT

Apart from security issues, war-torn societies and countries face immense challenges in rebuilding damaged critical infrastructure. Existing post-conflict recovery frameworks mainly focus on social impacts and mitigation. Also, existing frameworks for resilience to natural hazards are mainly based on design and intervention, yet, they are not fit for post-conflict infrastructure recovery for a number of reasons explained in this paper. Post-conflict peacebuilding can be enhanced when resilience by assessment (RBA) is employed, using standoff observations that include data from disparate remote-sensing sources, e.g. public satellite imagery, forensics and crowdsourcing, collected during the conflict. This paper discusses why conflicts and warfare require a new framework for achieving post-conflict infrastructure resilience. It then introduces a novel post-conflict framework that includes different scales of resilience with a focus on asset and regional resilience. It considers different levels of knowledge, with a focus on standoff observations and data-driven assessments to facilitate prioritisation during reconstruction. The framework is then applied to the transport network of the area west of Kyiv, Ukraine to demonstrate how resilience by assessment can support decision-makers, such as governments and multilateral financial institutions, to address infrastructure needs and accelerate financial and humanitarian assistance, absorb shocks and maximise infrastructure recovery after conflict.

1. Introduction

Post-conflict rehabilitation in war-shattered countries is a weighty and vital operation for restoring peace and security and assuring resilient and sustainable socio-economic development of the country and the region. War and conflict impose tremendous losses and impacts at multiple scales and sectors, including physical infrastructure, which is targeted during hostilities (Hay et al., 2019). The ongoing war in Ukraine provides such an example of conflict costs; as of March 16, 2022, there was an estimated $100 billion of infrastructure damage alone, while total material damage was valued at $210 billion (Ciuriak, 2022) and counting. The immediate focus is on mobilising resources, in the absence of tax receipts, to fund government functions, pay public servants and maintain public services during the war. G7 finance ministers pledged $20 billion to “help Ukraine close its financing gap and continue ensuring the delivery of basic services to the Ukrainian people” (Group of Seven (G7), 2022). Since the conflict commenced on the 24th of February 2022, this financial gap increases by an average of $5 billion a day, due to the loss of critical infrastructure in a country with GDP of $155 billion. These losses include mainly direct damage to infrastructure, as currently reconstruction is limited. The total cost of rebuilding infrastructure, homes and businesses might amount to $1 trillion (Caon & Shehadi, 2022; UN News, 2022). International organisations, i.e. the World Bank, International Monetary Fund (IMF) and European Union (EU) and other individual countries and investors will play a leading role in reconstruction, however, they have their own rules and priorities

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(The Economist, 2022). Therefore, an objective and evidence-based resilience framework could facilitate a common course of action in peacebuilding.

Restoring damaged infrastructure is vital to peacebuilding and social resilience because effective infrastructure is the backbone of the recovery process and urban resilience, in conjunction with ecological and social resilience (Schlör et al., 2018) and sustainability (Yang et al., 2018). Based on the available literature, the recovery of a war-torn country after conflict and warfare (Kreimer, 1998; Watkins et al., 2017), and the achievement of its macroeconomic stability requires prioritising the rebuilding of physical infrastructure, with emphasis on transportation, energy, agriculture, and urban development. Apart from the restoration of physical infrastructure and facilities, the economic dimension of post-conflict reconstruction also involves providing relief assistance and re-establishing social and other services (Earnest, 2015). Such support should ensure the appropriate conditions for the private sector development, implementation of essential structural reforms for growth (Tzifakis, 2013) and more sustainable infrastructure (Watkins et al., 2017) to align with the Sustainable Development Goals of the United Nations and reduce urban vulnerability (Kyprianou et al., 2022). It is inevitable that governments will not initially achieve all the conditions required for the resumption of development. Likewise, reconstruction aid might be shaped by external organisations applying conceptual frameworks for new developments, however, these frameworks might be inappropriate for war-torn countries (del Castillo, 2008).

Reconstructing a war-torn country's infrastructure is an immense operation, which can benefit from recent advances in catastrophe and resilience modelling and the use of openly available data to better inform these models (Bujones et al., 2013). However, there are also challenges that must be overcome to successfully deliver such frameworks (Hoeffler, 1998). First, it is of paramount importance to have a practical resilience framework for the rebuilding and recovery of essential infrastructure, e.g. transportation, energy, water and communications. The framework must produce a recovery that is sustainable and well-informed based on (i) the evolving needs of the people, region and/or country, (ii) the changes in critical infrastructure use, importance and its repurposing, (iii) the priorities in reconstruction based on available funds and resources, and (iv) the risks of protracted-hostilities (Hay et al., 2019). The latter can prolong the recovery period because post-conflict, there are still security issues and hence infrastructure destruction may recur, affecting *social*, e.g. households, *economic*, e.g. firms and businesses, and *physical infrastructures*, e.g. bridges, roads, railway stations, hospitals and schools (Girod, 2015). Second, the framework must adapt available resilience theory, frameworks and tools (e.g. (Argyroudis et al., 2020)) to the needs and particularities of the post-conflict country and its state (Al-Saidi et al., 2020). Third, the resilience framework should fully deploy state-of-the-art technology to accelerate the identification of damaged assets and networks and hence facilitate targeted and well-informed decision-making in reconstruction operations (Fantini et al., 2020). Damaged assets can be identified systematically during the conflict to generate meaningful data and documentation of infrastructure condition, for example by monitoring damage using standoff techniques (e.g. satellite imagery) (Witmer, 2015; Casciati et al., 2017) and other technologies (Weir et al., 2019; Argyroudis et al., 2022; Knoth et al., 2018) and use of available maps and geospatial analysis to better design recovery of affected cities (Cariolet et al., 2019; Levin et al., 2018). The deployment of satellite imagery and social media crowdsourcing for assessing infrastructure disruptions has been extensively investigated in the past in the context of natural disasters (Kryvasheyeu et al., 2016; Imran et al., 2013; Chen & Hutchinson, 2007) and environmental impact (Arturo Mendez Garzón & Valánszki, 2020) or location and extent of building damage as a result of conflicts (Boloorani et al., 2021). These studies demonstrated the added value brought by aerial surveys to facilitate mainly identification or severity of damage (Chen & Ji, 2021) and very recently to enable adaptive recovery and prioritisation (Kottmann et al., 2021). In such cases, the focus in typically on power grids, dynamic replanning based on damage information updates and tweaking recovery actions may be applicable. However, the focus of these papers is on buildings or energy networks and does not integrate information from different sources (e.g. crowdsourcing). Yet, this intelligence from data can inform objectives, assessment and assist in setting priorities, which can then be leveraged during and after the conflict to accelerate decision-making for reconstruction and incentivise resilience financing. For example, this can facilitate re-building productive capabilities, infrastructure repair and reconstruction, strengthening governance and institutions, leveraging opportunities to connect to new markets, by reducing uncertainty and clearly communicating the case for supporting the reconstruction. Communicating this sensitive information is often challenging though as it should not be available in the public domain.

Nevertheless, to date, we have a lack of fit-for-purpose resilience frameworks for post-conflict peacebuilding of critical infrastructure. Available post-conflict reconstruction frameworks mainly refer to social impacts and mitigation (Kottmann et al., 2021; Anderlini & El-Bushra, 2004; Maxwell et al., 2017) and do not provide adequate information on hard assets and infrastructure (Brown, 2002). The focus of reconstruction frameworks is, for example, on the impact of conflicts on livelihoods and displacement of populations, the role of social networks and the actions to ensure social well-being and inclusivity and to restore internal security (International Monetary Fund, 2022). There are a number of different actors who are providing financial support through various modalities including governments, international organisations, development finance institutions and non-governmental organisations. These organisations would aid reconstruction through official development assistance, concessional and non-concessional lending and other financing instruments and measures such as debt cancellation and budget support. Most support is in the form of government-to-government transfers. Each implies different financial terms and implications for the macroeconomy. In general, this refers to financial and humanitarian aid but not military assistance. For example, for the recent conflict in Ukraine, a range of pledges were made in the early months of the war notably by the European Union, European Bank for Reconstruction and Development, World Bank and the IMF. These stakeholders would benefit from such a framework to facilitate communication and mutual accountability between authorities of the affected country to better prioritise and target funds to support the rapid recovery of critical infrastructure (Clarvis et al., 2015).

This paper provides a resilience framework for damaged critical infrastructure that aims to incentivise recovery and peacebuilding in war-torn countries by facilitating improved management and decision-making. The framework's main novelty is that it introduces for the first time, resilience by assessment (RBA) in war-torn countries, i.e. the evaluation of affected critical infrastructure during the course of the conflict, in conjunction with resilience by intervention (RBI), i.e. post-conflict (Hynes et al., 2022; Mahoney et al., 2022) to accelerate decision-making and reconstruction. It is recognised that RBA has been broadly used in natural hazards that occur over long periods of time leading to infrastructure damage, thereby enhancing resilience (Cariolet et al., 2019). Nevertheless, the new RBA framework that is introduced by this paper, entails standoff assessments and the collection of data for enhancing post-conflict resilience. The framework deploys data, concerning the topology and typology of critical assets, while RBI uses post-conflict ground-validated data and forensics to evaluate infrastructure reliability, capacity, operability, and evolving demands. Proactive resilience by design (RBD) (Mahoney et al., 2022) for civil infrastructure is not considered here as it is unrealistic in case of conflicts. This framework is applied to a case study transport network in the area of Kyiv, Ukraine to demonstrate how resilience by assessment can support decision-making and post-conflict policy and practice in infrastructure recovery. This research will lead to further developments by extending its applicability to other assets including infrastructure systems interdependencies, in conjunction with evidence and data made available when safe access to infrastructure will be possible.

2. Challenges to existing resilience frameworks

Since the emergence of resilience in civil engineering, introduced in Bruneau et al. (2003), several frameworks have been developed for diverse systems and services (Ganin et al., 2016; Bostick et al., 2018; Linkov et al., 2021). The frameworks focus on the resilience of communities and cities (Cimellaro et al., 2016; Castillo et al., 2022), critical infrastructure exposed to floods (Nofal & van de Lindt, 2021; Mitoulis et al., 2021) or earthquakes (Cardoni et al., 2022; Bocchini & Frangopol, 2012; Cimellaro et al., 2021; Argyroudis et al., 2020), including deterioration effects (Yang & Frangopol, 2019). Other frameworks concern multiple hazards (Argyroudis et al., 2020; Li et al., 2020), including dependencies (Balakrishnan & Cassottana, 2022; Guidotti et al., 2016) and propose representative resilience metrics (Sharma et al., 2018; Fuggini & Bolletta, 2020; Argyroudis, 2022) based on documented past events (Zorn & Shamseldin, 2015). Building from the above studies, this paper provides a new and urgently needed post-conflict resilience framework for critical infrastructure in war-ravaged countries. This framework has significant challenges and differences from the established frameworks, and introduces innovations as discussed below:

The resilience by assessment (RBA), as described in Section 4. This is a major knowledge gap for achieving a well-informed and rapid post-conflict reconstruction of critical infrastructure. Existing resilience frameworks for critical infrastructure are applied mainly to natural hazards such as earthquakes and climate stressors, e.g. floods. Thus, RBA's practicality and impact are low in natural hazard resilience frameworks compared to RBD and RBI, because the duration of these events is relatively short and thus provides a minimum opportunity for RBA. However, in power grids, adaptive strategies might be applicable by adjusting solutions during the recovery based on updated information and evidence of the network condition, based on standoff observations and data. Yet, this is not typical or common in transport infrastructure, for example, roads, bridges or tunnels, which have low redundancies and the design of restoration measures precedes their application and is very rarely tweaked or adapted during the recovery phase. This is due to the lack of adaptiveness for typical tenders, contracts and procurement processes in the construction industry.

Assess the type and dispersion of infrastructure damage, e.g. as a result of shelling and antagonistic attacks (Ängskog et al., 2018), which is substantially different in outcome and extent from the damage that is encountered by other stressors (Tang & Hao, 2010). Conflict and resulting destruction intensity can be nation-wide, with variable intensities that do not follow certain attenuation laws, which is the case for natural hazards. In a post-conflict resilience framework, damage mainly concerns the visible, above-the-ground components and infrastructure assets, e.g. bridge superstructures, building facades and roofs, and water tanks, while the impact on foundations or underground structures, e.g. pipelines, is significantly smaller. From a network topology point of view, this information is less accessible for many infrastructure systems, partially or fully buried under the ground, and hence assessment of its structural and operational capacity during conflict is very challenging, if not impossible. Another peculiarity is that preventive measures are not relevant to -conflict resilience frameworks e.g. strengthening of transport infrastructure against attacks similar to strengthening against natural hazards (Lagos et al., 2020). Nevertheless, concepts of game theory can be used for defending e.g. electric power grids against attacks (Holmgren et al., 2007). This is substantially different from other frameworks, e.g. climate adaptation prior to natural hazard occurrences (Rattanachot et al., 2015). Regarding dispersion of infrastructure damage during conflict, this may be segregated within large areas, regions and/or the entire country. The damages can be extensive, including numerous critical assets, e.g. bridges, hospitals, transport hubs such as ports, airports and railway stations, and communication towers. Such infrastructure may be targeted as part of plotted assaults or defence actions and deliberate incapacitation, which are difficult to predict (Mattsson & Jenelius, 2015), e.g. blowing up critical bridges and release of water from dams to block military advances (Kumar, 1997). Thus, anthropogenic attacks lead to damage by intelligent opponents, have different memory and are less random compared e.g. to climate hazards (Ängskog et al., 2018). Also, conflict leads to widespread and on some occasions nation-wide damage, while damage induced by natural hazards is more localised in specific areas and regions.

Differentiate emergency planning during and after the conflict. Planning needs to be adapted and varies based on the conflict duration, protracted hostilities, societal needs and military operations. These distinctions are not needed for emergency planning after natural hazards, which occur over shorter timeframes and are typically followed by interventions underpinned by federal civil protection mechanisms, and are likely to be fully functional for supporting the rehabilitation process.

The post-war recovery measures are driven by the target of 'life preservation first' and the changes in the functional purpose of certain assets and networks. This means increasing the redundancy of the network and prioritising this over its efficiency (Ganin et al., 2017; Linkov et al., 2022), thus safeguarding the functionality of the society in periods of protracted hostilities, as opposed to designing for increased efficiency of a few assets. For example, in energy systems, a usual practice against high-impact low-probability events is to make the network bigger by adding redundant power transmission and distribution routes to safeguard the infrastructure against external shocks (Panteli et al., 2017). Regarding infrastructure repurposing, post-war recovery measures might be substantially different from the ones after natural hazards, because people fled and/or changed habits, thus the framework incorporates the emergent use and functional purpose of critical infrastructure. This may include reduced capacity needs, variable mobility patterns and different demands in certain areas.

A post-conflict framework must incorporate new political conditions and constraints. Existing frameworks presume available national capacity for reconstruction and rehabilitation, sufficient financial resources and technical assistance, reconstruction expertise, and manpower and materials for reconstructing damaged assets. However, in post-conflict countries, political decisions, acceptance of peace-building by the people, or rejection of foreign aid (e.g. not allowed to enter the country) and support by international organisations, will determine policies (Seneviratne et al., 2015) and post-war resilience. These factors will define the lag time in recovery, which may be substantially longer than the recovery period after natural hazard occurrences.

Fig. 1 illustrates the main differences between the resilience models for natural hazards (a) and conflicts (b). The main differences between these two models concern: (i) the duration of the hazards where natural hazards (e.g. earthquakes, floods) the majority of which are usually abrupt in comparison with a war conflict, which lasts longer; (ii) the unique opportunity to reduce the lag time and thus accelerate RBI by deploying RBA while the conflict is still ongoing. RBA has less practicality and significance for certain natural hazards such as floods, earthquakes or tsunamis, which occur over short periods of time. Nevertheless, RBA is valuable in low evolving natural hazards such as prolonged winds affecting energy grids. It is noted that during normal operation infrastructure operability degrades, and the pace of degradation depends on the robustness and redundancy of the network. Also, Fig. 1(a) shows the case where an external shock (e.g. cyber-attack) or natural hazard (e.g. earthquakes) reduces suddenly the performance of infrastructure, resulting in a system performance similar to the so-called resilience triangle. However, there are cases where the perturbation develops over longer periods of time. For example, fatigue due to wind-induced long-term vibrations, yet these perturbations are part of Life Cycle Analyses and hence concern mainly the assessment of lifecycle sustainability (Yang & Frangopol, 2019). This behaviour of the system, reflected in Fig. 1(b), has been approximated by researchers using a

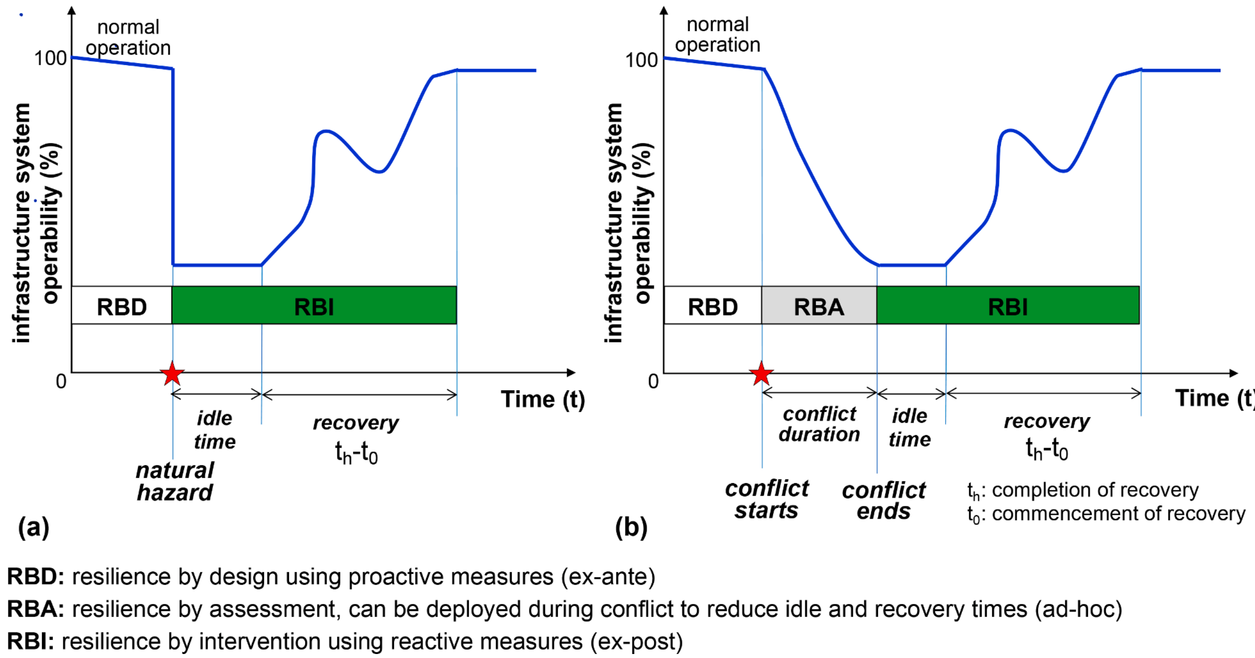

Fig. 1. Typical resilience models for abrupt natural hazards (a) and conflicts (b).

resilience trapezoid as it includes the slow performance degradation after the event. These approaches have been applied and adopted in most critical infrastructures, including for example power systems where a comparison of the resilience triangle and trapezoid can be found in Panteli et al. (2017).

Fig. 1 demonstrates that the recovery phase differs substantially for hazards of different nature, but this comparison is not the focus of this paper. This section explained why substantial deviations and adjustments are needed for existing resilience thinking, to evolve and support a robust resilience-based peacebuilding framework. It is clarified that RBA is distinct from absorption in this resilience framework. The framework of this paper is described in detail in Section 3. Nevertheless, some infrastructure systems might be positively impacted by RBA, which requires time for the integration of data into the resilience models. Such systems are power systems and distribution networks, where infrastructure operability might be decreasing over longer periods of time, e.g. prolonged heatwaves and/or wildfires impact on energy networks.

3. Post-conflict resilience framework

The resilience framework must account for different spatial scales of resilience, i.e. national, regional/network and asset. Decision-making and prioritisation for the recovery of the network can influence the restoration of a single asset and vice-versa. Also, physical dependencies (connectivity) between bridges, roads, railways, transport hubs (railway stations, airports) and Service Providing Nodes (SPNs) and critical facilities such as hospitals, should be taken into account. Fig. 2 illustrates the proposed resilience framework for critical infrastructure recovery, using a case study in Ukraine, with a detailed description below.

This framework can be easily adopted and applied to most infrastructures. In fact, the UK National Infrastructure Commission (National Infrastructure Commission, 2020) encourages critical infrastructure operators and owners, such as energy, water, communications, etc., to develop and apply such frameworks for their resilience assessment, quantification and enhancement. In energy systems, for example, the different nodes in Fig. 2 can be representing the electrical substations (as the railway stations) which are acting as the connection of the transmission lines (as the roads, railways and bridges) transferring energy from the generation stations to the end-users.

3.1. Levels of knowledge of infrastructure condition and demand

Three **levels of knowledge** for infrastructure condition and demand assessment are identified. Level 1 (L1) refers to the topology, typology and physical connectivity between critical infrastructure assets and SPNs within the region (e.g. connectivity between power generation stations, substations, transmission lines and customers in energy systems). L2 refers to the case where details are available, leading to further engineering knowledge, e.g. knowledge of the infrastructure capacity (for example, energy transmission system capacity), which depends on the condition of the asset, prior to the conflict and after any damage was caused by external stressors, e.g. shelling. L2 also includes the engineering demand for this structure, e.g. the required load-bearing capacity due to emergency and normal traffic anticipated on a bridge post-conflict (short- medium- and long-term), or the expected energy demand to flow through a transmission network corridor (during and post-conflict). L3 describes dependencies between the asset and other social factors, functionality demands and resilience of the supply chain for the construction materials, e.g. the required traffic volume for a bridge and the number of patients that would need to be transferred to a hospital or the transfer of goods and/or materials to and from regional hubs and the affected assets. With regard to asset-level assessments, the framework of this paper focuses on L1 as a means to improve RBA, while L2 and L3 are expected to be available post-conflict to support RBI. However, as the network is a graph, the node dependencies can be derived from topology, using traffic engineering and the context of transport assets. Therefore, at the network level L1 and L3 overlap and/or interact, yet the use and demand might change substantially after conflict. Also, different **sources of knowledge** available before, during and after conflict are identified in this framework. These sources of knowledge constitute the core of the proposed framework and are discussed in detail in Section 4.

3.2. Steps of the framework

At a national level (**step 1**) it is expected that certain funds would be allocated per region/province and spent to maximize the country's

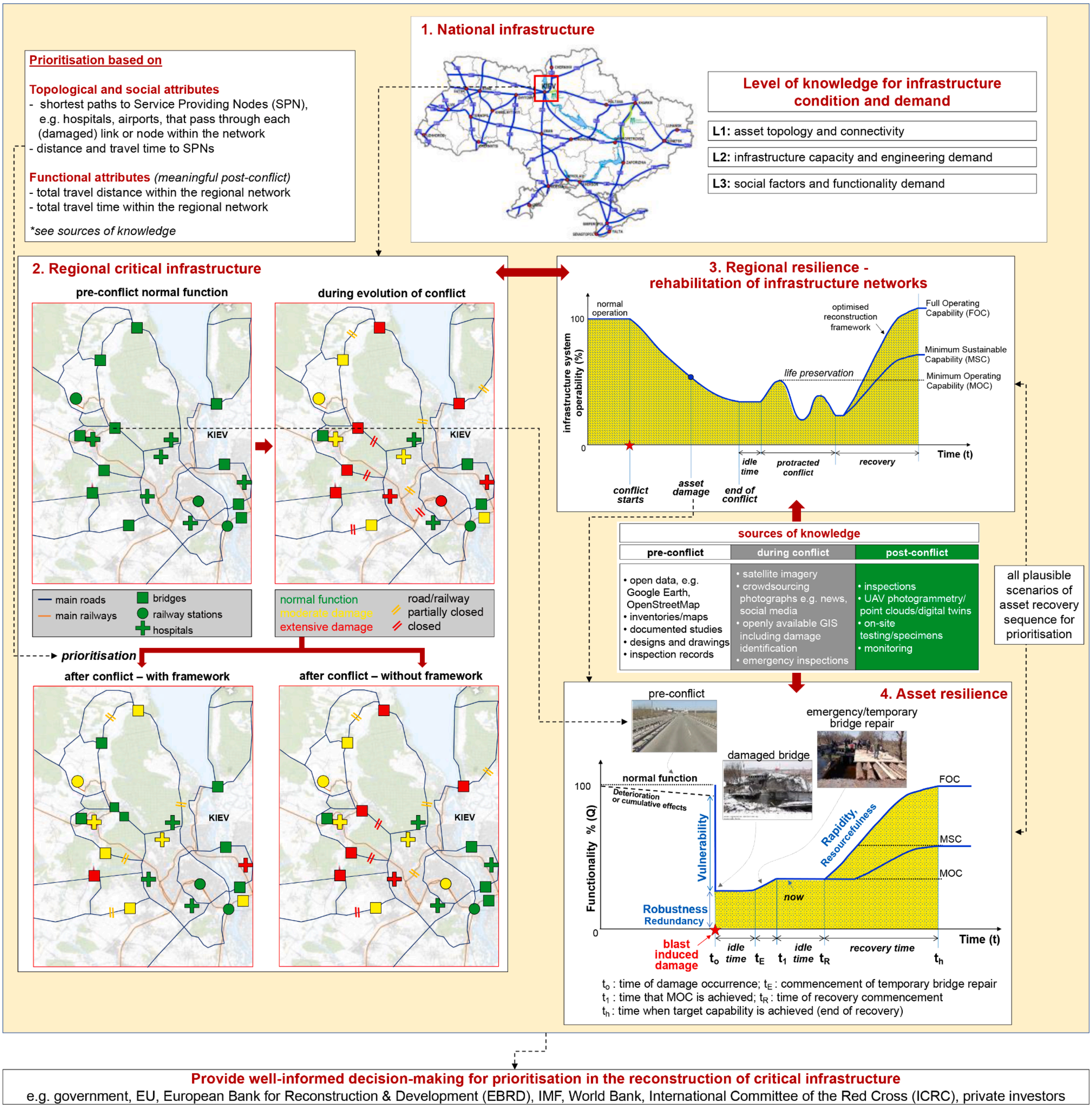

Fig. 2. Resilience framework for rebuilding critical infrastructure after conflict.

resilience. **Step 2** shows the region west of Kyiv in Ukraine including the towns of Irpin, Hostomel, Bucha and Stoyanka. The map in Step 2 of Fig. 2 plots the main roads and railways, bridges, railway stations, and hospitals. Arguably, their recovery is more efficient when prioritisation is conducted and hypothetically shown here as the case of 'after conflict-with framework', as opposed to the case of 'after conflict-without framework', where fewer assets and connections have been recovered. This prioritisation requires identifying the scenario that produces the maximum resilience for the network as per step 3 (below) and the asset as per step 4 (below).

In **step 3**, the resilience of the region is shown as a function of time including the beginning and the end of the conflict, the period where no reconstruction occurs (idle time), followed by a period of protracted hostilities during which the functionality of the region is expected to be fluctuating. The recovery may achieve different levels of performance, which are described by three target capabilities (as per (Hay et al., 2019)), i.e. *minimum operating capability* (MOC), which is most likely the one corresponding to emergency planning, *minimum sustainable capability* (MSC) that corresponds to the performance that can be maintained by the available resources in the post-conflict country,[1] and *full operating capability* (FOC), similar or higher (as a result of adaptation measures and interventions) to the original. The decision-making for recovery prioritisation depends on a number of attributes which differ significantly from the ones relating to natural disasters (Zamanifar & Hartmann, 2021). For example, for transportation infrastructure, post-disaster recovery commonly uses topological, social, and functional attributes (Merschman et al., 2020) as well as the criticality of the asset

[1] In energy systems the "sustainable capability" refers to the capability of an energy infrastructure to sustain a minimum level of functionality for a period of time, before full restoration takes place.

and damage level. Similarly, in energy systems, different attributes are utilised for post-disaster recovery, for example, the criticality of the loads to be served or disconnected (e.g. hospitals, and police stations) (Moreno et al., 2022). For RBA purposes, we emphasize the topological and social attributes, i.e. shortest paths to SPN (e.g. hospitals, airports) that pass through each (damaged) link or node within the network and the distance and travel time to SPNs. Functional attributes such as the total travel distance within the regional network or total travel time within the regional network are meaningful for RBI. However, during the conflict, the origin-destination (O-D) patterns and total travel times are irregular, and thus, not appropriate for assessments. Hence, in this paper, topological and social, concerning connectivity to SPNs, and financial attributes through the reconstruction cost, are considered. These attributes are used to identify the resilience optimum based on which the asset recovery sequence is objectively prioritized.

Step 4 refers to the resilience of a single asset which depends on the assessment and decision taken at the network level. The figure illustrates the case of a bridge which has been damaged during the conflict. After the damage, the restoration of the asset will depend on the extent of damage, the duration of the conflict, the resources allocated for the restoration post-conflict and/or during the protracted conflict period, and the level of target capability (see step 3). The following terms are mentioned in the figure of step 4 and further discussed by Mitoulis et al. (2021): (1) Vulnerability and Robustness, which depend on the bridge type, e.g. continuous or simply-supported deck (Argyroudis & Mitoulis, 2021), the material, and the component(s) damaged by the blast. (2) Redundancy, which depends on the alternative structural components to transfer loads on the ground (aka statically indeterminate structure), while for the network depends on the alternative routes. (3) Resourcefulness, depends on the availability of needed resources and services and the capacity to mobilise them for post-disaster recovery. (4) Idle time depends on the conflict's duration, accessibility, responsiveness and prioritisation. (5) Rapidity & recovery time is influenced by the bridge importance, available resources and policies, the extent of damage, and restoration tasks, amongst others. It is noted that the standoff assessments, which are described in Section 4, are extremely valuable to all steps described above, as they can accelerate the recovery by rapid resilience assessments at the regional and asset level. This resilience framework is expected to enable well-informed decision-making by all interested parties to prioritise infrastructure recovery efforts before and during the reconstruction phase.

4. The value of standoff and ground-validated data

Existing post-conflict peacebuilding emphasises reactive measures during the reconstruction period (Hay et al., 2019). Yet, effective implementation of post-conflict operations requires intensive monitoring during the course of the conflict. For example, the World Bank (Kreimer, 1998) highlights the need to allocate sufficient resources for monitoring and assessment, so that peacebuilding funds are allocated during peace negotiations. Also, monitoring and standoff observations can reduce lag time due to waiting to assess infrastructure conditions until after the conflict resolves because access to the ground during the conflict is challenging and high risk. Lag time could also be the result of authorities having different priorities or the state of damage will not remain final and war-induced destruction is often ongoing, with not much perspective on what will become of the asset's condition when it is finally safe to intervene.

We argue that this hurdle can be overcome by leveraging openly available data, which can be collected by standoff observations, in conjunction with forensics and crowdsourcing. Such data can be obtained from disparate sources available prior to the conflict, e.g. traffic data, satellite imagery, inventories, maps, inspection records, previous studies, and during the conflict and protracted hostilities, e.g. satellite imagery, aerial photography, complemented by phone metadata and news or social media crowdsourcing. This data, when deployed by the framework described in Section 3, can accelerate critical infrastructure assessments, and facilitate faster post-conflict decision-making and recovery and hence more effective financing for resilient and sustainable peacebuilding of cities focused on the safety and security of the society, inclusive of political processes, core government functions and the rule of law (OECD, 2018).

This defines the framework of this paper, which is enhanced by resilience by assessment (RBA). More specifically, each one of the steps described above can benefit from data available prior to, during, and after the conflict. For example, **prior to the hazard/conflict**, open data from Google Earth and OpenStreetMaps and previous studies, see e.g. (IMPACT, 2020; Ivanenko, 2020) for Ukraine, can provide useful information for L1 assessments of asset topology and connectivity at a national and regional level. This may also include information about assets' functionality, e.g. traffic volumes of bridges. Accessibility to designs, drawings and inspection records is less likely due to data protection security and potential loss of data during conflicts. For example, data could inform the design of adaptation measures to climate change (Smith et al., 2021). However, this is less relevant to conflicts, where RBD for critical infrastructure is highly unlikely because planners typically do not consider future conflicts in infrastructure design. Nevertheless, planners can develop and leverage openly available data to fulfil RBA, **during the hazard/conflict and protracted hostilities**. For example, satellite imagery can be used to identify the location of affected infrastructure, the extent of damage, and, in conjunction with openly available mapping services, the connectivity to other SPNs and alternative routes (Weir et al., 2019; Witmer, 2015; Fakhri & Gkanatsios, 2021; Levin et al., 2018).

Available data from crowdsourcing, e.g. photographs from social media, research platforms which monitor damage in areas that experience conflict (see e.g. UNITAR[2]) and news broadcasts, can be used to validate satellite reported damage and improve theaccuracy of assessments. Freely available tools such as Google Earth or street views and photographs of Google Maps can be used to measure the dimensions of assets that are damaged, define their geometry, as well as the type of the asset. Further, reports by infrastructure owners and operators, such as power system operators, can be utilized to assess the damage to critical infrastructures, such as power stations and power lines. This can assist in further validating the type and extent of damage as well as the potential duration and cost of reconstruction. **Post-conflict validation** can be achieved with inspections on the ground, which, in case of reduced accessibility, can be enhanced by UAV imagery-derived point clouds, digital twins (Loli et al., 2022; Loli et al., 2022; Greenwood et al., 2019), and monitoring to deliver accurate representations of the physical asset and its surrounding environment.

This intelligence is invaluable for several reasons, including the recovery modelling of the asset and the region/province after the conflict and the ability to optimise decision-making and resource allocation. At the **network level**, openly available maps and data can underpin the planning of reconstruction to improve the resilience of the region. For example, Fig. 3 below shows the level of information that can be obtained by openly available data, e.g. locations of main towns, bridges, roads, and SPNs such as hospitals and airports. Based on this information, adequately accurate planning of alternative scenarios for the region's reconstruction and resilience can be achieved, i.e. the optimisation of the infrastructure operability, for given resources. Further information is provided in the case study of Section 5.

At the **asset level**, open data can provide valuable and practical evidence. Fig. 4a to 4d show the information that is openly available in Google Maps for an overpass bridge along T1019 at the junction with M06 (E40) (Kalynivka, Kyivska, Oblast). From this data, (i) the location of the bridge that was established to be damaged was identified

[2] United Nations Institute for Training and Research, https://www.unitar.org/maps/countries/107

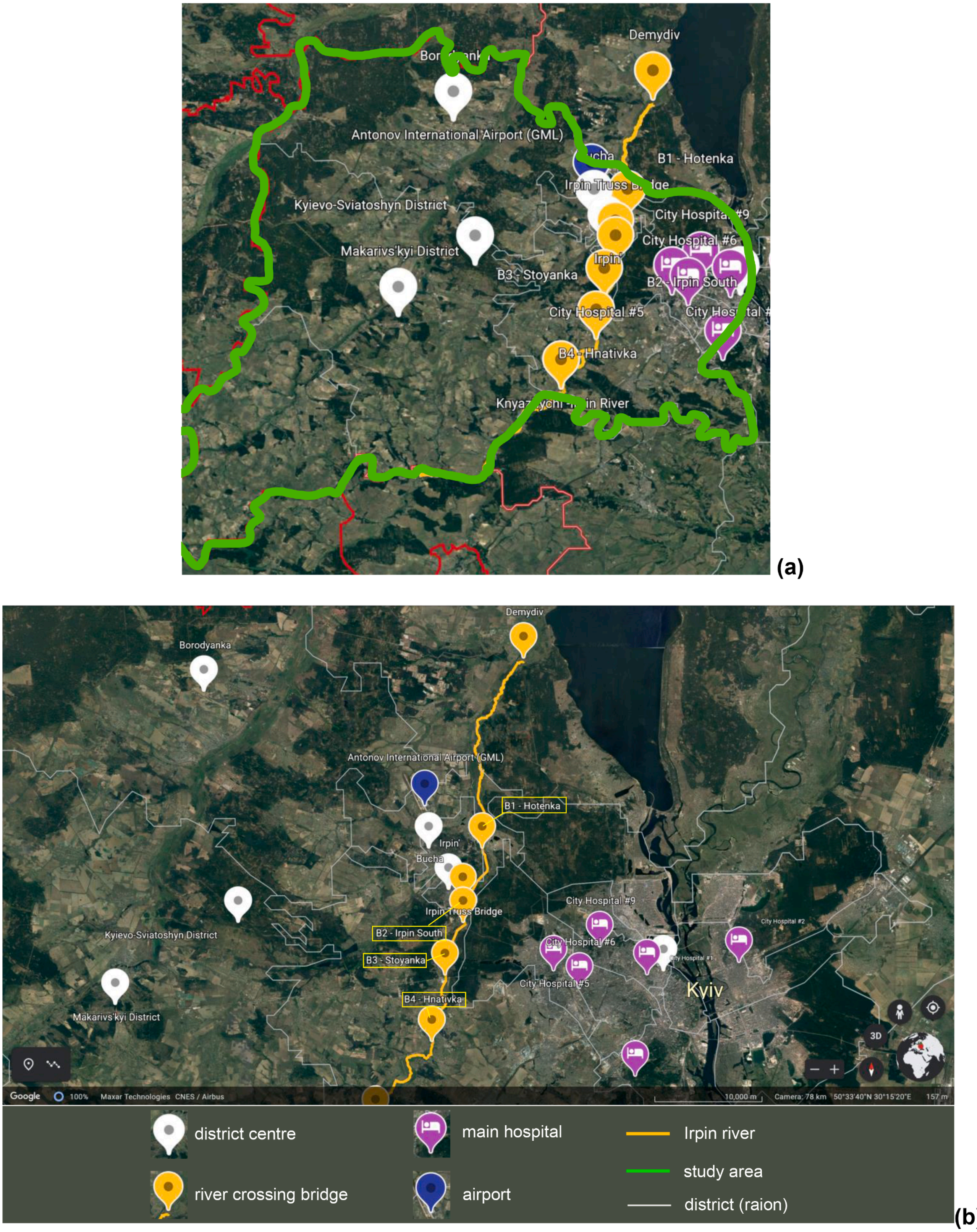

Fig. 3. (a) The boundaries of the chosen region (green line) for the case study (see Section 5). (b) A project on Google Earth map showing the west of Kyiv area in Ukraine, illustrating the locations of (i) Irpin River; (ii) damaged river crossing bridges; (iii) centres of Districts (Raions); (iv) main hospitals and the Antonov airport.

(50°25′02.9″N 29°48′03.7″E), (ii) the length, width and depth of its deck were measured (i.e. length: $4 \times 21.75\ m = 87$ m, width: 15.5 m, depth: 1.2 m), (iii) the type of the bridge was identified (straight, continuous slab deck on one line of 14 elastomeric bearings, double bent pier with cap beam, backfills retained with concrete blocks), and hence estimates can be provided for (iv) the cost of repair, that was estimated at €4,05 million, assuming a cost of €3000/m^2, which is the typical cost for the types of bridges that were damaged and identified based on

Fig. 4. The level of knowledge for RBA enhancement (a) bridge topology, (b) Google Street View of the bridge elevation and geometry, (c) view of the bridge typology (deck, pier and embankment), (d) the expansion joint of the bridge (used to assess the length of the spans), (e) the satellite images before and during conflict (Copernicus Sentinel-2 10 m optical imagery), (f) and (g) bridge damage crowdsourcing from social media (some sentences were intentionally deleted to exclude comments from users that take sides and ensure anonymity).

openly available data (WSDOT Bridge Design Manual M 23–50.21, 2022) and engineering judgement. Also, it is assumed that the replacement bridges will be constructed using expedient and cost-effective solutions, e.g. prefabrication with I-beam bridges and cast in situ methods, (v) repair tasks (e.g. replacement of deck, bearings and partial reconstruction of piers), and duration of demolition/replacement of part of the bridge (see (Mitoulis et al., 2021)). Also, (vi) the connectivity of this bridge with the surrounding area and SPNs can be identified using openly available data. In Fig. 4e the satellite images are shown for the same bridge before and during the conflict. Complementary data and validation can be achieved in some instances from crowdsourced data and evidence, for example, LinkedIn and Facebook, as shown in Fig. 4f and 4g. From these figures, the extent and type of damage can be identified. If the information regarding damage is insufficient, alternative methods can be used, e.g. super-resolution enhancement of high-resolution images like Sentinel-2 or Landsat 8/9 (Cresson, 2022; Lanaras et al., 2018) and/or SAR interferometry (Markogiannaki et al., 2022) to measure non-visible damage and deformation, and translate these into potential structural damage.

For the case of the west Kiev – Irpin bridges, satellite data from Copernicus Sentinel-2 satellites were used. Optical Sentinel-2 imagery was investigated using a comparison of frames before and after the estimated date of possible damage or collapse. The frames selected cover the timespan between February the 2nd and March the 10th, 2022. This data is available on the Copernicus Open Access Hub.[3] Sentinel-2 multispectral optical imagery has a ground resolution of 10 m for Red, Green, Blue and Near-Infrared bands and a temporal revisit of ~5 days. Sentinel-2 imagery is an improvement over the previously best-available open and public satellite imagery (i.e. the Landsat 8 with 15 m ground resolution and 16 days of revisit) that can assist in rapid damage assessment by mostly visual inspection at service-providing nodes. Due to the limitations of ground pixel resolution to 10 m, no detailed identification of damage or small-size features, e.g. structural components of critical assets, can be performed. However, such data and identification techniques can be useful in case of severe or complete damage to an asset. Resolution enhancement techniques, such as super-resolution (Cresson, 2022) can greatly improve visual interpretation and recognition of structural features and damage on the bridges (Fig. 4e) but should be applied with caution, as false features or unwanted artefacts may be introduced. Commercial Very High Resolution (VHR) optical imagery with a resolution of 0.3–2.0 m is more suitable for assessing damage on structures such as bridges, but there are still limitations to its use, for example, (a) non-open source with a high cost of acquisition, (b) no regular revisit schedule and temporal coverage, (c) smaller swath width (usually <20 km) than open Sentinel-2 and Landsat 8/9 satellites (185–290 km) that enables capture of a larger region, (d) geometric distortions due to oblique acquisition angles (common features in rapid response frames).

The importance of disparate data sources in resilience assessments depends on a number of parameters. For example, the reliability, accuracy, uncertainty, and accessibility of data sources are all very important for a consistent and applicable resilience framework, yet, when the latter refers to conflicts some data are protected due to confidentiality, and hence they are not openly available. These disparate sources provide heterogeneous data of different value and significance toward resilience assessments. For example, data from social media might provide high-definition photographs of assets, however, might not be reporting the exact location or not provide information for the entire asset, e.g. only local damage of a long-span bridge. Similarly, satellite imagery of low resolution can be used for damage identification, yet does not provide adequate accuracy for the type of damage and the components of the asset. Therefore, it is of paramount importance to develop holistic frameworks and practical tools, for successfully fusing multimodal heterogeneous data, to inform resilience modelling.

In conclusion, using publicly accessible data for RBA during the conflict can increase resilience as shown in Fig. 5 in a qualitative manner. The top plot illustrates the resilience model of a region affected by conflict without considering RBA, while the bottom plot shows the case where RBA is employed. First, the idle time without RBA is likely to be substantially longer because the network and asset level engineering data will be insufficient for planning. Thus, it is expected that the prioritisation process would be more time-consuming due to the lower level of asset and network understanding. Therefore, the duration of RBI will be shorter when RBA is employed. Second, RBA will enhance the resilience during the period of protracted hostilities as emergency planning will be more efficiently designed, leading to shorter times of restoration and increased operability. The benefit of RBA is also shown in a quantitative manner based on the definition of resilience which is proportional to the area under the resilience curve (see also Eq. (1)). The area under the bottom plot in Fig. 5 is larger ($A_2 > A_1$), meaning that resilience is higher when RBA is employed. Furthermore, this framework can offer a vulnerability assessment of the restored assets and thus reduce the duration of the restoration, if data is made available. This is an approach that assumes an ideal reconstruction environment, yet, the operability level of infrastructure could remain dynamic and unknown until the conflict is deterministically settled, which imposes great uncertainties in RBI.

5. Application of the framework in the west Kyiv province, Ukraine

This section is an application of RBA as per the framework described in Fig. 2. This case study demonstrates how damage assessments for critical assets and lifelines, in conjunction with resilience analyses based on standoff observations during the course of the conflict, can accelerate recovery. The application is based on the very recent destruction of transport assets in west Kyiv province in Ukraine, during which several bridges along the Irpin river were extensively damaged. The location and the size of the study area were selected considering the spatial distribution of the damaged assets, the strategic importance of the area, the proximity to the capital and the dependency to its emergency (e.g. hospitals) and other services (e.g. financial, educational) as well as the availability of data for the needs of this case study. This application assumes recovery to full operating capability (FOC), however, the framework can be applied by aiming at higher or lower levels of operating capability (e.g. minimum sustainable or minimum operating capability) depending on the post-conflict needs. Although critical infrastructure protection was recently introduced in Ukraine's national security policy, this was mainly at a conceptual level and for peacetime conditions (Sukhodolia, 2018).

5.1. *Steps for resilience-based decision-making in transport infrastructure recovery*

In what follows, the steps of the proposed resilience framework are described in detail, including the evolution of network performance for which the process described in Merschman et al. (2020) was used (see Appendix A). The method is extended in this paper because limited resources (funds, materials, workforce) will be available post-war. Hence, the cost of reconstruction is paramount and for this reason, resilience is normalised with the reconstruction cost (see Eqs. (1) to (5) below). The results of this analysis will inform decision-making and prioritisation for rebuilding Ukraine, based on new and communicable resilience metrics. The four steps described below were followed:

Step 1: A number of damaged critical transport assets (riverine bridges of Irpin river) have been identified as the main source of traffic disruption between Kyiv and the areas of Irpin and Bucha, Kyievo-Sviatoshyn district, Makarivs'kyi district, and Borodyanka

[3] https://scihub.copernicus.eu/

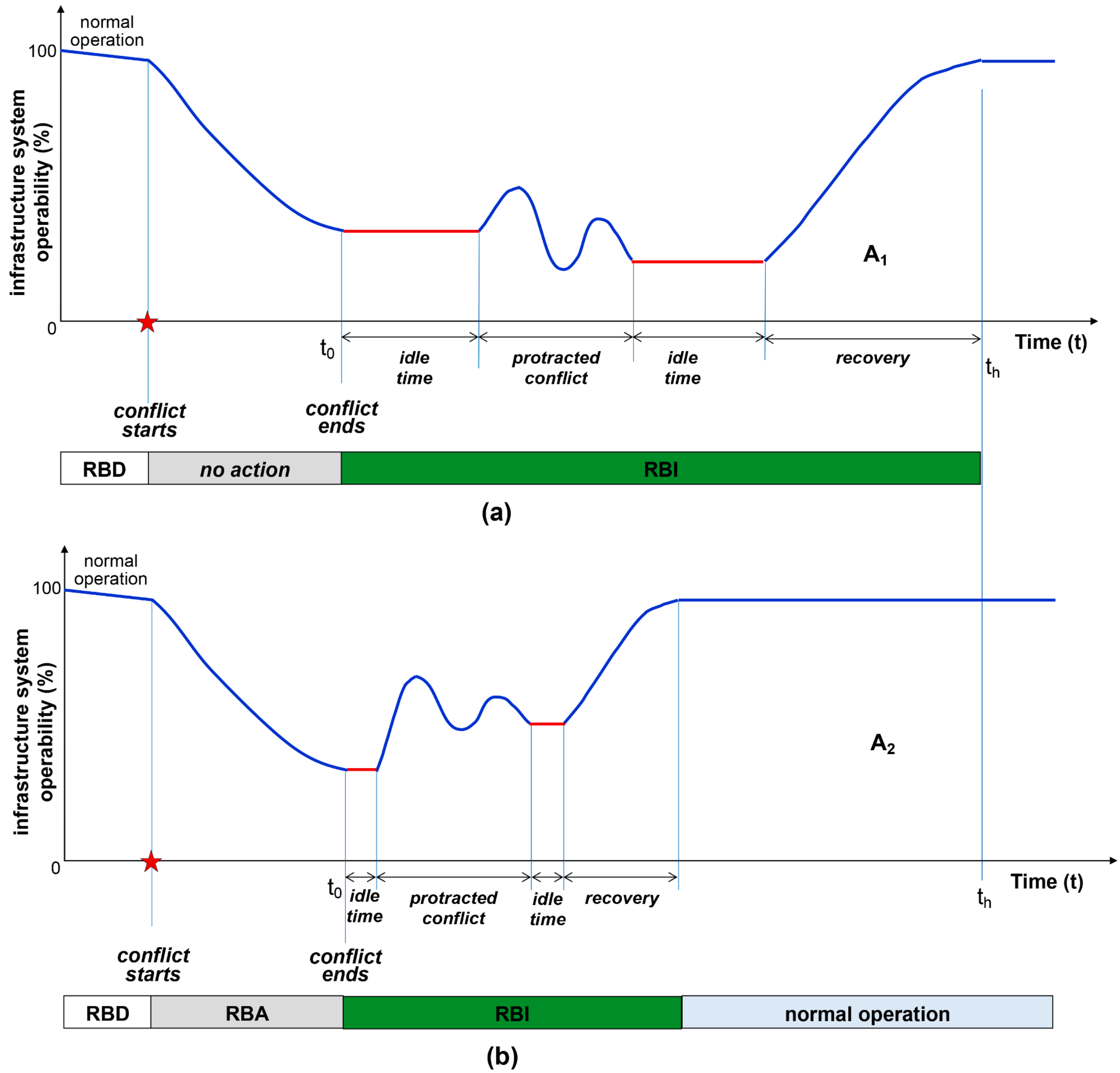

Fig. 5. The resilience model of a region affected by conflict (a) without considering RBA, (b) consider deployment of RBA.

district, as shown in Fig. 3. This case study assumes level 1 (L1) of knowledge, and a prioritisation based on topological, social and functional attributes. The boundaries of the districts were taken from Hijmans (2015).

Step 2: Based on the openly available traffic data (i.e. Google traffic), the main roads connecting the aforementioned areas to central Kyiv were found to be operable. However, several bridges were extensively damaged, and they are closed. Temporary bridges are currently serving emergency traffic (MOC). For the needs of this application, four critical damaged bridges (B1 to B4 shown in Table 1) were selected as the main links between the areas shown in Table 2 and Kyiv. The damage to these bridges was validated by satellite imagery and crowdsourced data (see Section 4). For each one of the representative areas of Table 2, four alternative routes were identified, including travel time and distance (topological and functional attributes). Each one of these routes passes over bridges B1 to B4. For example, paths 1.1, 1.2, 1.3 and 1.4, from Irpin/Bucha to Kyiv, are passing over B1, B2, B3 and B4, correspondingly. The

Table 1
Geometry, cost and restoration time for the case study bridges.

Bridge	Coordinates	Spans	Length (m)	Width (m)	Area (m^2)	Reconstruction cost* (€)	Restoration time** (days)
B1. Hotenka	50.5533, 30.2843	3	140	26	3640	10,920,000	328
B2. Irpin South	50.4910, 30.2590	3	120	22	2640	7920,000	238
B3. Stoyanka	50.4469, 30.2351	2	90	30	2700	8100,000	243
B4. Hnativka	50.3911, 30.2177	4	100	10	1000	3000,000	90

* cost estimated at 3000 €/m^2 for conventional RC/PC bridges.
** B4 was the reference bridge, while the restoration time was adjusted based on the area for B1, B2, B3, by a factor of 3.64, 2.64, 2.70, respectively.

Table 2
Representative Origin-Destination (O-D) and alternative routes through the case study bridges.

O-D traffic flow	Alternative routes	Roads along the route	Distance (km)	Time (min)	Serving bridge	Road on bridge
1. Irpin/Bucha to Kyiv, 16,674 vehicles/day*	1.1	E373	29.87	40	B1	E373
	1.2	P30	32	42	B2	P30
	1.3	P30, E40	50	90	B3	E40
	1.4	P30, T1038, P04	50.5	75	B4	P04
2. Kyievo-Sviatoshyn District to Kyiv 5201 vehicles/day*	2.1	E373	49.8	60	B1	E373
	2.2	E40, P30	34	43	B2	P30
	2.3	E40	26	31	B3	E40
	2.4	P04, E40	39.2	45	B4	P04
3. Makarivs'kyi District to Kyiv 4792 vehicles/day*	3.1	E40, E373	82	90	B1	E373
	3.2	E40, P30	64	60	B2	P30
	3.3	E40	56.2	52	B3	E40
	3.4	E40	67.6	64	B4	P04
4. Borodyanka to Kyiv 5779 vehicles/day*	4.1	E373	58.4	63	B1	E373
	4.2	P30	56.2	60	B2	P30
	4.3	E373, E40	61.5	62	B3	E40
	4.4	E373, E40	76.3	75	B4	P04

* 10% of the population.

shortest routes in Table 2 are shown in Fig. 6, connecting the four main areas west of the Irpin river with the capital Kyiv. For each district of origin, the population was found from online census data (State Statistics Committee of Ukraine, 2022), and the daily traffic was considered to be 10% of the population. This assumption does not affect the resilience assessment; thus, if a different percentage was assumed, the resilience assessments would remain unchanged for this case study. It is also noted that the destination chosen, i.e. Kyiv, represents the position of the main hospitals that serve these areas (social attributes).

Step 3: Regarding the regional resilience, which drives the rehabilitation of the infrastructure network, it is assumed that the infrastructure system operability, bounces back to its full operating capability (FOC). No other scenarios for minimum sustainable capacity (MSC) or minimum operating capacity (MOC) were examined. The network performance (NP) was assessed for all alternative bridge repair sequences (i.e. 24) by calculating Ci, corresponding to functional and topological measures (see Eqs. (A1) to (A4) in Appendix A). In this paper, we present results for the following six sequences, which envelope all the solutions: Sequence 1 (S1): B1, B2, B3, B4; Sequence 2 (S2): B4, B3, B2, B1; Sequence 3 (S3): B2, B1, B3,

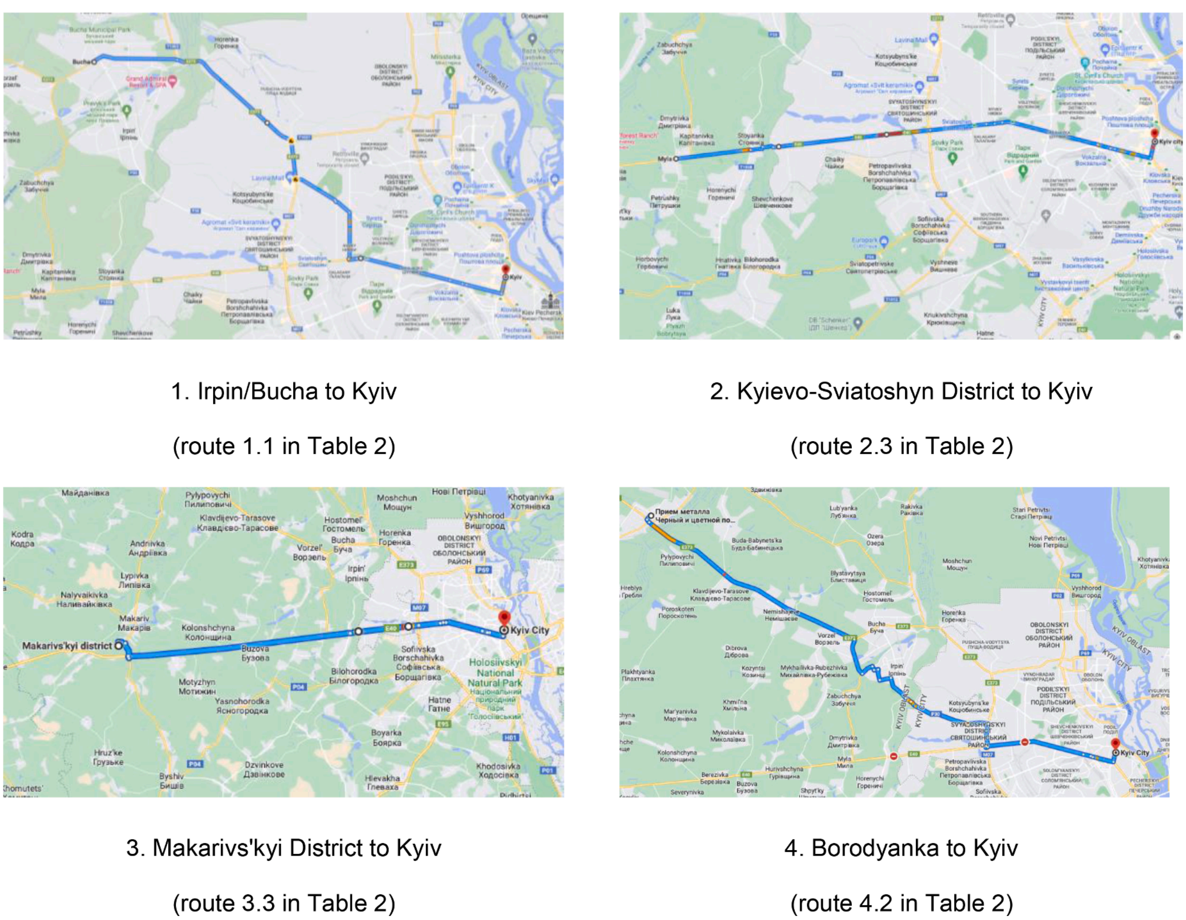

Fig. 6. Shortest routes for the four representative connections of the case study.

B4; Sequence 4 (S4): B4, B3, B1, B2; Sequence 5 (S5): B3, B2, B1, B4; Sequence 6 (S6): B2, B3, B1, B4.

For the functional measures (C1, C2, see Eqs. (A1) and (A2) in the Appendix) the total travel time and distance for all vehicles with no bridge damaged and when one or more bridges are damaged were computed for each step of a given sequence of restoration. The topological measure (C3, see Eq. (A3) in the Appendix) was based on the total number of shortest paths on each bridge for a given combination of damaged and functional bridges. For example, when the sequence of B1, B2, B3, B4 was considered, the factors C1, C2, and C3 are calculated for the following cases: (i) only B1 is open, (ii) B1 and B2 are open, (iii) B1, B2 and B3 are open, (iv) B1, B2, B3 and B4 are open. NP is calculated based on C1, C2 and C3 considering variable weighting factors (γ_1, γ_2, γ_3) ranging from 1 to 5. These values are reasonable based on literature (Merschman et al., 2020) and were used to examine the sensitivity of NP to topological and functional parameters, which take a minimum value of 1.0 (small influence) to 5.0 (dominant parameter). In post-disaster decisions for bridge repair, these weights reflect different priorities of the operators and decision-makers during the reinstatement of the network's operability, i.e. whether functionality or topology is more important. The social measure described by C4 (e.g. travel time from different zones to hospitals) is meaningless in this particular application because the city of Kyiv as the destination also represents the location of the main hospitals, hence the same O-D can be used, Also, this paper is not dealing with emergency planning but with reconstruction. Hence, C4 is equal to 1.0.

Step 4: First, the asset functionality is negligible, hence, all bridges B1 to B4 were considered to be completely damaged. The target functionality of reconstruction was considered to be FOC, thus, the asset will be reconstructed and will offer its full functionality, equal to the original one. For the assessment of the network performance, no idle time was considered and the post-damage NP was considered to be 0.1. The time of reconstruction is considered proportional to the area of the deck (see the last column in Table 1). For example, the baseline restoration time of 90 days was assumed for B4 which has a total plan area of 1000 m^2 and hence the reconstruction time of B1, which has a plan area of 3640 m^2 is estimated 3.64 times longer, i.e. 328 days. This approximation was based on the results of a recent survey for bridge reconstruction, which provided a mean duration of 36.6 days of one span. This duration is adjusted here to 30 days per span, to take into account the size of the deck area, which is approximately 20% smaller compared to the survey's baseline (Mitoulis et al., 2021; Mitoulis & Argyroudis, 2021).

This paper focuses on the infrastructure network of a war-ravaged city, therefore for the case study resilience is defined as the ability of the network to recover from the effects of asset failure (bridges) in a timely and cost-effective manner. Towards this, Eq. (1) expresses the resilience index $R(t_h)$, as per (Cimellaro et al., 2009):

$$R(\mathrm{th}) = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} NP(t)dt \tag{1}$$

where t_h - t_o is the time window for which $R(t_h)$ is estimated, e.g. for the case study analysed here and for the total duration of each one of the sequences S1 to S4, t_h is 898 days and t_0=0, while NP(t) is the time-variant network performance. Note that the evolution of $R(t_h)$ means that t_h depends on the commencement and the duration of B_i restoration.

The cost of each bridge is given by Eq. (2):

$$\mathrm{Cb_i} = \mathrm{A_i c} \tag{2}$$

The cumulative cost for a given sequence Si is given by Eq. (3) and the normalised cumulative cost is calculated based on Eq. (4):

$$\mathrm{Cbp} = \sum_{i=1}^{p} Cbi \tag{3}$$

$$\mathrm{Cni} = \frac{Cb_p}{\mathrm{Cb}_{tot}} \tag{4}$$

Hence, the cost-based resilience $R_c(t_h)$ is calculated as per Eq. (5):

$$\mathrm{Rc(th)} = \frac{R(t_h)}{\mathrm{Cn}_i} \tag{5}$$

where:

$\mathbf{A_i}$ is the plan area of the bridge deck given in Table 1, i.e. total length times the width of the deck,

c is the unit cost for the construction of 1 m^2 of the deck, which is fixed at 3000 €/m^2 for conventional RC/PC bridges,

$\mathbf{Cb_p}$ is the cumulative sum of bridge reconstruction costs, i.e. the sequence of partial sums of the given sequence of bridges,

p is the bridge that is being under restoration for the identified sequences of this case study (S1 to S4) and for which the resilience of the network is assessed,

$\mathbf{R_c(t_h)}$ is the value of the cost-based resilience index of the network at the time $\mathbf{t_h}$ that bridge **p** is restored.

It is noted that for $i = p$, Cn_i=1, therefore the maximum value of the cost-based resilience index $R_c(t_h)$ is identical to the resilience index estimated when the cost is not taken into account. This value is always smaller than 1 due to the loss of functionality because of the damage that leads to functionality loss.

5.2. Results and discussion

In this section, the results of the bridge repair sequence prioritisation are presented in terms of network performance vs time (Fig. 7a and 7b, assuming equal weighting factors γ_1=γ_2=γ_3= 1.0). Also, the resilience index (Fig. 7c and 7d) and resilience normalised with cost vs time are presented (Fig. 7e and 7f). Two different scenarios for the traffic were assumed. The first assumes traffic per O-D is proportional to the population (Fig. 7a, c, e), which is considered to be more realistic. The second assumes the same traffic flows per O-D (Fig. 7b, d, f). The R values reported in Fig. 7a and b, are the resilience metrics taken as the maximum values of plots in Fig. 7c and d, and calculated based on Eq. (1), for a time window of 898 days, which is the cumulative restoration time for all bridges B1 to B4 (Argyroudis, 2022). It is noted that it is common to allow traffic on a bridge even when the bridge is under repair and the bridge has not gained its full structural capability. The linear increase in the network functionality assumes that the reinstatement models illustrating the post-conflict gain of the traffic capacity of the network is linear, i.e. allowing limited traffic on bridges that are damaged, but under repair, which corresponds to e.g. emergency and minimum operational traffic. A stepwise model for the network performance would be unrealistic, as this would practically simulate the case where a bridge is fully restored before allowing any traffic on it (Mitoulis et al., 2021).

It is observed that the sequences with the highest performance in the first phase are the ones which commence with the reconstruction of B2 (see sequences S3 and S6). This result is showing the importance of the bridge in the south Irpin and justifies from a strategic point of view, the severity of the attack in this region. The sequence with the best network performance is depicted with the black line (S6) and reaches the complete restoration before any other sequence, while it maintains the highest network performance in comparison with the other sequences throughout the entire hypothetical recovery. The performance of the sequences is not changing dramatically for the two adopted traffic flow models (Fig. 7a and b), except for the network performance of S1, while S2 and S4 have increased more swiftly network performance when traffic was considered to be equal distributed in all O-D. Also, the shapes

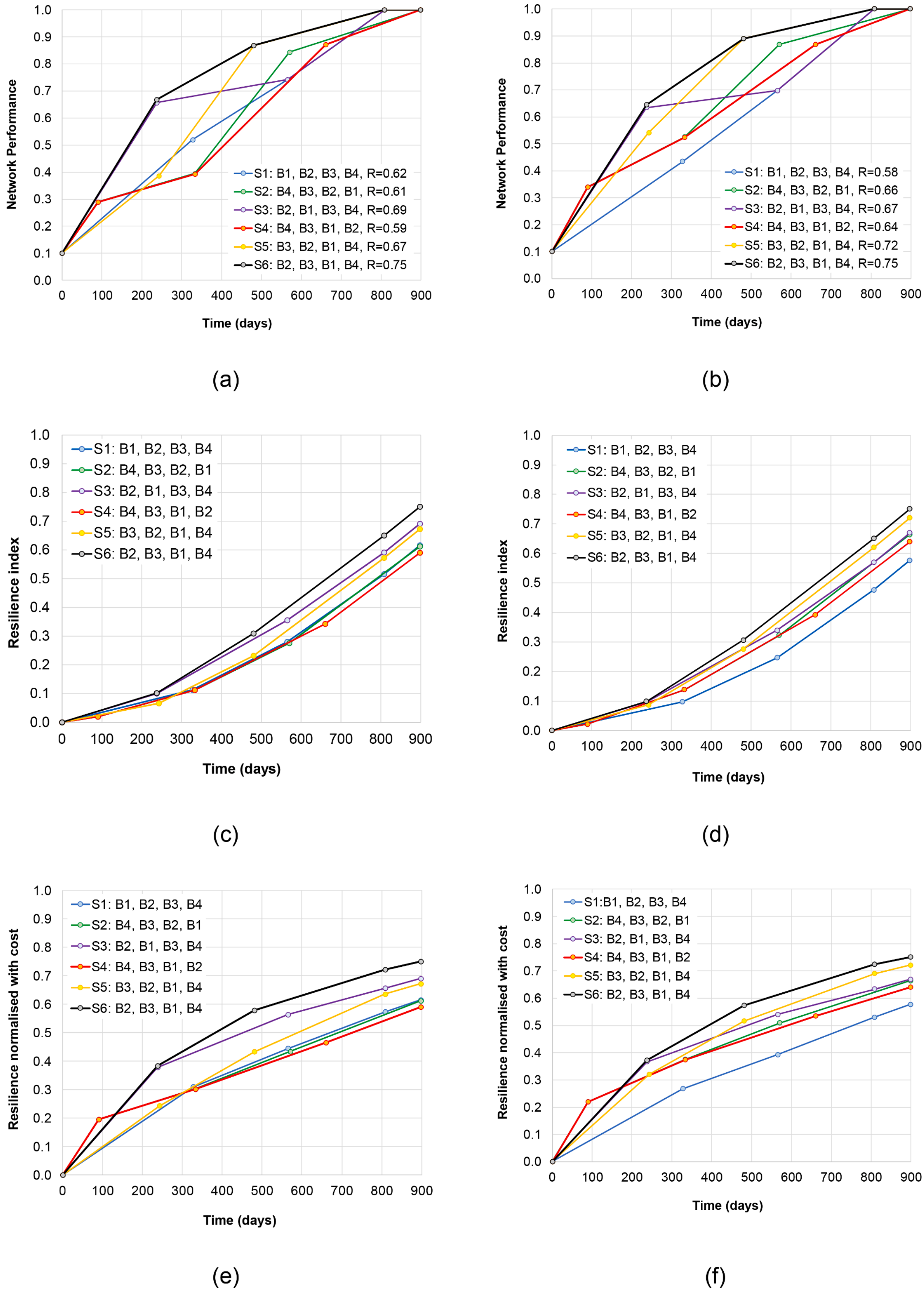

Fig. 7. Evolution of network performance (a, b), evolution of resilience index (c, d) and resilience normalised with cost over time (e, f), for equal weighting factors (γ_1=γ_2=γ_3= 1.0) and traffic proportional to the population (a, c, e), or equal traffic flow per O-D (b, d, f).

of the restoration curves remain the same, except for S5, which is closer to a linear behaviour until the value of NP=0.9 and the restoration is more gradual for the assumption of equal traffic flow. This is the reason why it is exhibiting also better resilience performance than the S3 in Fig. 7f, regarding its position in Fig. 7e. Fig. 7e and f justify that the best (S6) and the worst (S1 and S4) solutions regarding the repair sequence in terms of network performance maintain their position also in terms of cost. However, B4 is the bridge that has the smallest area and hence the lowest cost, and the smallest repair duration. This justifies the reason that S4 is the best sequence in the first phase when resilience is normalised with cost.

To better understand the importance of combined resilience and cost, Fig. 7 also shows the evolution of the resilience of the network over time considering the network performance and the network resilience accounting for the cost. All cases assumed γ_1=γ_2=γ_3= 1.0. The comparison of Fig. 7c vs 7e and 7d vs 7f, yields that for limited budgets (e.g. post-war) restoration of bridge B4 first, i.e. considering Sequence 4, (S4): B4, B3, B1, B2, would maximise the short-term resilience within the first 100 days, whereas long-term resilience is maximised by Sequence 6 (S6): B2, B3, B1, B4. Therefore, the cost-based resilience index is informative in that it shows the evolution of the network resilience for a given sequence of bridge restoration, which also indicates the optimum allocation of resources (including financial) for a more expedient achievement of resilience in the short-term and/or the longer-term.

Fig. 8 illustrates the network performance vs time assuming variable weighting factors, aiming to better understand the sensitivity of NP and resilience for the analysed sequences when the focus is on functionality (γ_1, γ_2) or topology (γ_3). The sequence with the highest performance for all the scenarios with the different weighting factors remains S6. The variation of the weighting factors seems to have affected negatively more S2 and S4, which in all scenarios have the lowest performance in terms of resilience (R). S5 is also affected, at least until the first bridge repair, as the network performance remains relatively low. For the best sequence (S6) that leads to the highest resilience index R = 0.75 (Fig. 7a), the NP reduces when unequal weighting factors are considered, with the worst scenario being γ_3=5.0, for which $R = 0.61$. Thus, it is also observed that factor γ_3 (which refers to the topology) is having the highest impact on the sequences, both for the scenarios with different weighting factors. The increase of γ_3 is found to lead to a reduction of R up to almost 30%. The increases of γ_1 and γ_2 lead to similar results regarding the sequences of restoration.

Apart from the in-series reconstruction of bridges (i.e., one by one), a parallel reconstruction of at least two bridges at the same time was also examined corresponding to the sequences P1 to P6 (see Fig. 9). The assumption of the P1 to P6 scenarios is that there is no limitation to the availability of labour, and hence, the simultaneous reconstruction of two bridges, e.g. B1+B2, would require a total time equal to the maximum of the reconstruction time of the two individual bridges, i.e. 328 days. The time window for which the resilience index was estimated in all cases was equal to the one used for S1 to S6, i.e. 898 days, meaning that for P1 to P6, the network performance is NP=1 after day 571. Fig. 9 shows that the resilience index is increased when parallel reconstruction of more than one bridge takes place. Indicatively, the maximum achieved R for S6 was 0.75, whereas for P6 this value was estimated equal to 0.84. From the examined sequences of reconstruction, the one that was influenced mostly was the resilience of S5 (R is increased from 0.67 to 0.84) and the ones that were less affected was S3 (R is increased from 0.69 to 0.75). Yet, the resilience-based decision-making for reconstruction would not be altered significantly for the case of the parallel reconstruction as still S6 and P6 stand with the highest long-term resilience. The sequence when considering in series construction with decreasing resilience is S6, S3, S5, S1, S2, S4, while when parallel reconstruction is considered, the optimal sequence is P5 or P6, P1 or P3, P2 or P4 for a time window of 898 days.

5.3. Limitations and future directions

The current study focuses on the resilience assessment of the transport network due to war-induced disruptions and the subsequent destruction of main critical infrastructure, such as bridges. The proposed approach assumes an ideal reconstruction environment, yet a number of factors and correlations that impose significant uncertainties will have to be included in future research. These include infrastructure interdependencies, risks of protracted hostilities, post-conflict demand, available functionality and potential repurposing of infrastructure, post-conflict changing needs of businesses, people and communities, social and organisational reforms, budget limitations and political decisions for the reconstruction.

Also, from a financial point of view, the implications of conflict are also macro-critical, as they destabilise balance of payments (BOP) positions, disrupt trade and financial flows, and hinder the development of productive resources. Government resources are important because of market failures during and following conflicts. Commercial lenders will likely not be interested in investing in infrastructure reconstruction because of the sums involved and the uncertainties related to returns on investments. Governments can help de-risk such investments, but it is likely that external public funding would be essential to support conflict-affected states to achieve macroeconomic stability, enhance resilience, strengthen governance, and promote inclusive growth (International Monetary Fund, 2022).

A potential association between the resilience capacities of the transport network and the supply chain of the construction sector will also have to be taken into account (Blagojević & Stojadinović, 2022). The proposed framework will be extended in the future to include case studies regarding railways, schools and energy infrastructure, as numerous energy and water plants have been either severely or completely damaged, along with their interdependencies with the healthcare system (e.g. hospitals, crucial supply chain for the healthcare system). Moreover, resilience planning can take into consideration the calculation of the recovery time of potential insurgent actions and the constant presence of hybrid threats, especially in regions of high and diachronic geopolitical instability, where the end of a major conflict doesn't secure the end of the tension between the two or more in conflict parts. Also, the huge progress in the usage of UAV or special cameras for the inspection of damaged structures can lead to a new source of information for more accurate resilience modelling, by providing more information for the level of knowledge 2 (L2). The proposed resiliency framework can be examined under the prism of post-war urban planning frameworks (Kyprianou et al., 2022), to associate actions and support efficient decisions, also considering this in conjunction with other hazards (Wang & van de Lindt, 2022).

6. Conclusions

This paper introduces a new framework for the quick recovery of war-torn countries. The framework focuses on resilience-informed prioritisation of infrastructure assets. Thus, this framework has the potential to enable better cooperation amongst different decision-makers, donor agencies, institutions, interested parties, and other aider countries on the basis that infrastructure peacebuilding prioritisation is performed with an objective prism, that is the swift recovery of the area. Thus, the framework can contribute to the mitigation of influences of own rules and priorities in post-war reconstruction for the benefit of the societies. The main novelty of this paper is that it introduces resilience by assessment (RBA), i.e. enhancing resilience assessments during the conflict, in conjunction with resilience by intervention (RBI), i.e. post-conflict for critical infrastructure asset reconstruction. Three levels of engineering knowledge are introduced by the framework, while the application entails data-driven standoff assessments using, e.g. satellite imagery and crowdsourced evidence, with emphasis on the topology and typology (L1) of damaged critical assets. Engineering capacity and

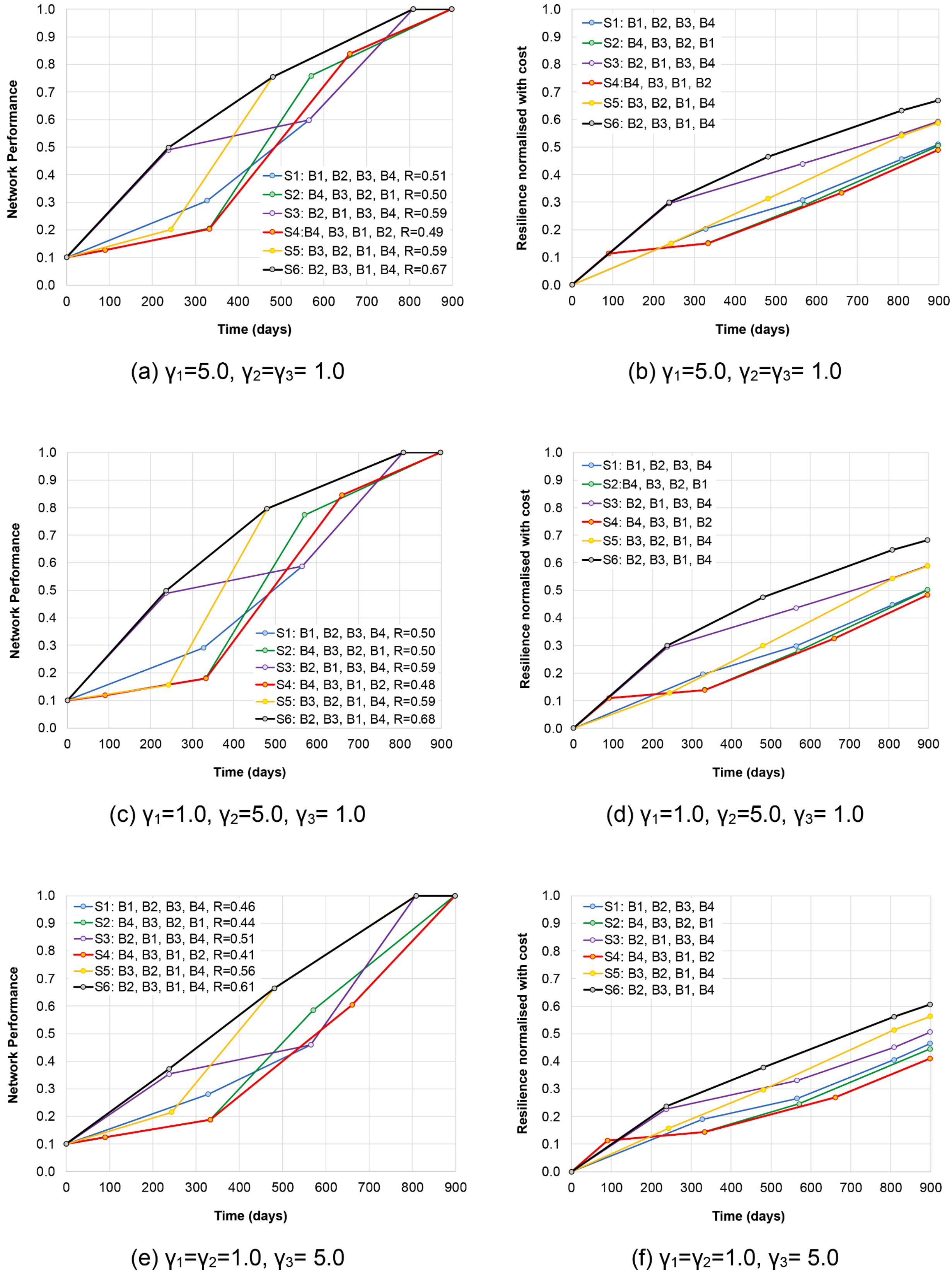

Fig. 8. Evolution of network performance (a, c, e) and resilience normalised with cost over time (b, d, f), for different weighting factors and traffic proportional to the population per O-D.

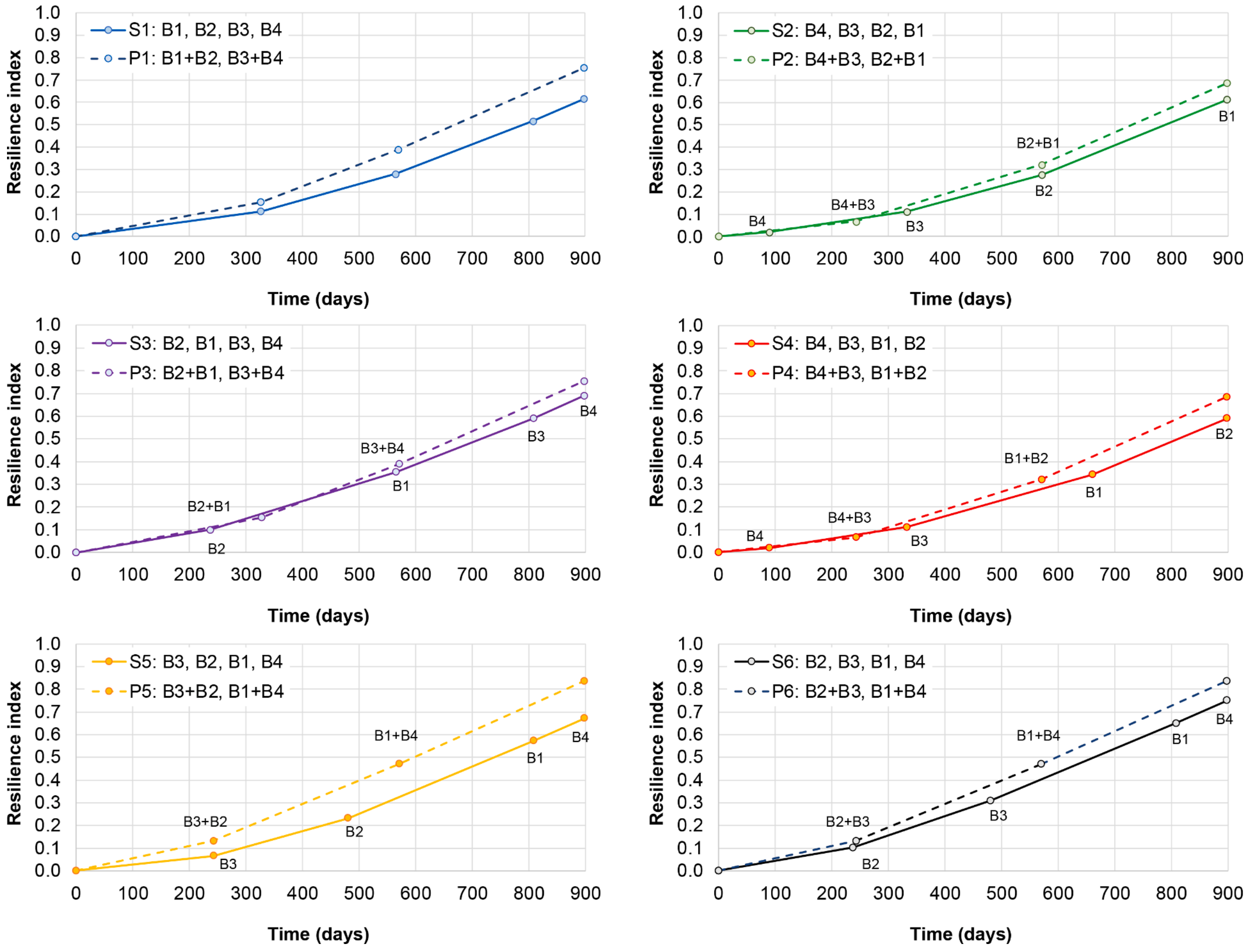

Fig. 9. Comparisons of the evolution of the resilience index of the network considering in series (continuous lines S1 to S6) and parallel (dashed lines P1 to P6) bridge reconstruction sequences for equal weighting factors (γ_1=γ_2=γ_3= 1.0) and traffic proportional to the population.

demand (L2) and social factors and functionality demand (L3) will be employed post-conflict in support of RBI.

The proposed framework was implemented for the prioritisation of bridge repair sequence for a transport network based on optimised resilience and cost. A number of possible prioritisation scenarios were examined in the areas west of Kyiv in Ukraine. In-series and parallel reconstruction strategies were examined. The sequence of bridge reconstruction S6: B2, B3, B1, B4 is qualified as the most efficient for the in-series strategy, leading to the greatest resilience index. If at least two bridges are reconstructed in parallel an 8 to 20% increase in the resilience index is achieved, while sequences P5: B3+B2, B1+B4 and P6: B2+B3, B1+B4 are the most efficient ones.

The analysis also spotlighted the significance of the South Irpin bridge (B2), for the most efficient restoration of the transport network. This is justified by the fact that the sequence scenarios B3 and B6, which prioritised the restoration of this bridge were found to have the greatest resilience indexes, while those which didn't prioritise the reconstruction of B2 exhibited lower performance. The two assumptions for the traffic flow per origin-destination (O-D) showed no great differentiations in the shape and the performance of restoration sequence scenarios. Moreover, the comparison of the sensitivity of the transport network performance to its functionality (expressed by γ_1 and γ_2) and asset topology (expressed by γ_3), yielded that the topology factor γ_3 had the highest impact on network performance and R, as its increase from 1 to 5 led almost all the sequence scenarios to a decreased network and resilience performance. The increase of the γ_1 and γ_2 respectively led to a reduction of the resilience R in comparison with the case where all γ were taken equal to 1. This reduction of R ranges between 9 and 30%, when γ_i increases from 1 to 5. The case study included some approximations, such as the traffic flow (step 2), the sequence of restoration and the weighting factors of the functional and topological measures (step 3). Yet, the assumptions made are based on expert judgement, and hence the comparative results would not change significantly if different values were assumed.

Disclaimer

The views and opinions expressed in this article are those of the individual authors and not those of the U.S. Army, the OECD or other sponsor organisations.

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.

Data availability

Data will be made available on request.

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Appendix A

The following equations by Merschman et al. (2020) were used for the assessment of network performance (NP) in the case study of Section 5.

$$C_1 = 1 + \gamma_1 * \frac{\mathrm{TTD}_i - \mathrm{TTD}_0}{\mathrm{TTD}_0} \tag{A1}$$

where,

C_1 = functional measure factor for total travel distance (TTD),

TTD_i = the TTD with one or more bridges being closed because of damage,

TTD_0 = the TTD with all bridges being functional, and γ_1 = a weighting factor.

$$C_2 = 1 + \gamma_2 * \frac{\mathrm{TTT}_i - \mathrm{TTT}_0}{\mathrm{TTT}_0} \tag{A2}$$

where,

C_2 = functional measure factor for total travel time (TTT),

TTT_i = the TTT for all vehicles when one or more bridges are damaged,

TTT_0 = the TTT with no bridge damaged, and γ_2 = a weighting factor.

The total travel time (TTT) and total travel distance (TTD) where taken from GoogleMaps considering minimum times and distances for each O-D (e.g. see Fig. 6).

$$C_3 = 1 + \gamma_3^* \frac{\sigma(v)_0 - \Sigma_{k=1}^{n} \sigma(v)}{\Sigma_m^{k=1} \sigma_{ij}} \tag{A3}$$

where,

C_3 = topological measure factor,

$\sigma(v)$ = the total number of shortest O-D paths (see Table 2) on bridge v for a particular combination of damaged bridges,

$\sigma(v)_0$ = the initial number of shortest paths that pass through all bridges under consideration given that all are functional,

σ_{ij} = the total number of shortest paths that exist from i to j (origin-destination points),

n = the number of bridges under consideration,

m = the total number of nodes that exists in the network, and

γ_3 = a weighting factor for the topological measure.

$$\mathrm{NP} = \frac{1}{C_1^* C_2^* C_3^* C_4} \tag{A4}$$

where NP is the network performance metric, and C_1, C_2, C_3, and C_4 are functional, topological, and social measure factors. C_4 was taken equal to 1.0 as the destination of the case study (Kyiv) coincides with the main hospitals.

References

Al-Saidi, M., Roach, E. L., & Al-Saeedi, B. A. H. (2020). Conflict resilience of water and energy supply infrastructure: Insights from Yemen. *Water, 12*(11), 3269.

Anderlini, S.N., & El-Bushra, J. (2004). Post-conflict reconstruction. In: Inclusive security, sustainable peace: A toolkit for advocacy and action, 51–68.

Ängskog, P., Näsman, P., & Mattsson, L. G. (2018). Resilience to intentional electromagnetic interference is required for connected autonomous vehicles. *IEEE Transactions on Electromagnetic Compatibility, 61*(5), 1552–1559.

Argyroudis, S. A. (2022). Resilience metrics for transport networks: A review and practical examples for bridges. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering* (pp. 1–14).

Argyroudis, S. A., Mitoulis, S. A., Hofer, L., Zanini, M. A., Tubaldi, E., & Frangopol, D. M. (2020). Resilience assessment framework for critical infrastructure in a multi-hazard environment: Case study on transport assets. *Science of the Total Environment, 714*, Article 136854.

Argyroudis, S. A., & Mitoulis, S. A. (2021). Vulnerability of bridges to individual and multiple hazards-floods and earthquakes. *Reliability Engineering & System Safety, 210*, Article 107564.

Argyroudis, S. A., Mitoulis, S. A., Chatzi, E., Baker, J. W., Brilakis, I., Gkoumas, K., et al. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management, 35*, Article 100387. https://doi.org/10.1016/j.crm.2021.100387

Argyroudis, S. A., Nasiopoulos, G., Mantadakis, N., & Mitoulis, S. A. (2020). Cost-based resilience assessment of bridges subjected to earthquakes. *Intern Journal of Disaster Resilience in the Built Environment*.

Arturo Mendez Garzón, F., & Valánszki, I. (2020). Environmental armed conflict assessment using satellite imagery. *Journal of Environmental Geography, 13*(3–4), 1–14.

Balakrishnan, S., & Cassottana, B. (2022). InfraRisk: An open-source simulation platform for resilience analysis in interconnected power-water-transport networks. *Sustainable Cities and Society*, Article 103963.

Blagojević, N., & Stojadinović, B. (2022). A demand-supply framework for evaluating the effect of resource and service constraints on community disaster resilience. *Resilient Cities and Structures, 1*(1), 13–32.

Bocchini, P., & Frangopol, D. M. (2012). Optimal resilience-and cost-based postdisaster intervention prioritization for bridges along a highway segment. *Journal of Bridge Engineering, 17*(1), 117–129.

Boloorani, A. D., Darvishi, M., Weng, Q., & Liu, X. (2021). Post-war urban damage mapping using InSAR: The case of Mosul City in Iraq. *ISPRS International Journal of Geo-Information, 10*(3), 140.

Bostick, T. P., Connelly, E. B., Lambert, J. H., & Linkov, I. (2018). Resilience science, policy and investment for civil infrastructure. *Reliability Engineering & System Safety, 175*, 19–23.

Brown, R. H. (2002). Towards sustainable infrastructure: An adaptable model for post-war areas in developing countries. *Proceedings of the Institution of Civil Engineers-Municipal Engineer, 151*(3), 227–230.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., et al. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra, 19*(4), 733–752.

Bujones, A. K., Jaskiewicz, K., Linakis, L., & McGirr, M. (2013). *A framework for analyzing resilience in fragile and conflict-affected situations*. Columbia University SIPA.

Caon, V., & Shehadi, S. (2022). Entire cities will have to be rebuilt: How Ukraine is preparing for reconstruction. *Investment Monitor* accessed online 12/5/2022 https

://www.investmentmonitor.ai/special-focus/ukraine-crisis/entire-cities-rebuilt-ukraine-reconstruction-russia.
Cardoni, A., Borlera, S. L., Malandrino, F., & Cimellaro, G. P. (2022). Seismic vulnerability and resilience assessment of urban telecommunication networks. *Sustainable Cities and Society, 77*, Article 103540.
Cariolet, J. M., Vuillet, M., & Diab, Y. (2019). Mapping urban resilience to disasters–A review. *Sustainable Cities and Society, 51*, Article 101746.
Casciati, F., Casciati, S., Fuggini, C., Faravelli, L., Tesfai, I., & Vece, M. (2017). Framing a satellite based asset tracking (SPARTACUS) within smart city technology. *Journal of Smart Cities, 2*(2) (Transferred).
Castillo, J. G. S., Bruneau, M., & Elhami-Khorasani, N. (2022). Seismic resilience of building inventory towards resilient cities. *Resilient Cities and Structures, 1*(1), 1–12.
Chen, Y., & Ji, W. (2021). Enhancing situational assessment of critical infrastructure following disasters using social media. *Journal of Management in Engineering, 37*(6).
Chen, Z., & Hutchinson, T. C. (2007). Urban damage estimation using statistical processing of satellite images. *Journal of Computing in Civil Engineering, 21*(3), 187–199.
Cimellaro, G.P., Fumo, C., Reinhorn, A.M., & Bruneau, M. (2009). Quantification of disaster resilience of health care facilities. Technical Report MCEER-09-0009, Buffalo, NY.
Cimellaro, G. P., Arcidiacono, V., & Reinhorn, A. M. (2021). Disaster resilience assessment of building and transportation system. *Journal of Earthquake Engineering, 25*(4), 703–729.
Cimellaro, G. P., Renschler, C., Reinhorn, A. M., & Arendt, L. (2016). PEOPLES: A framework for evaluating resilience. *Journal of Structural Engineering, 142*(10), Article 04016063.
Ciuriak, D. (2022). *The economic consequences of Russia's war on Ukraine* (p. 11). Verbatim: CD Howe Institute.
Clarvis, M. H., Bohensky, E., & Yarime, M. (2015). Can resilience thinking inform resilience investments? Learning from resilience principles for disaster risk reduction. *Sustainability, 7*(7), 9048–9066.
Cresson, R. (2022). SR4RS: A tool for super resolution of remote sensing images. *Journal of Open Research Software, 10*(1). https://doi.org/10.5334/jors.369
del, Castillo (2008). *Rebuilding war-torn states: The challenge of post-conflict economic reconstruction*. New York: Oxford University Press Inc.. https://doi.org/10.1093/acprof:OSo/9780199237739.001.0001
Earnest, J. (2015). Post-conflict reconstruction – A case study in Kosovo: The complexity of planning and implementing infrastructure projects. *International Journal of Emergency Services, 4*(1), 103–128. https://doi.org/10.1108/IJES-02-2015-0009
Fakhri, F., & Gkanatsios, I. (2021). Integration of Sentinel-1 and Sentinel-2 data for change detection: A case study in a war conflict area of Mosul city. *Remote Sensing Applications: Society and Environment, 22*, Article 100505. https://doi.org/10.1016/j.rsase.2021.100505
Fantini, C., Morgan, G., Kumar, S., Adeoti, T., Reese, A., Schouten, P., & O'Regan, N. (2020). *Infrastructure for peacebuilding: The role of infrastructure in tackling the underlying drivers of fragility*. Copenhagen, Denmark: UNOPS.
Fuggini, C., & Bolletta, F. (2020). Identification of indicators, metrics and level of service for the resilience of transport critical infrastructure. *International Journal of Sustainable Materials and Structural Systems, 4*(2–4), 330–346.
Ganin, A. A., Kitsak, M., Marchese, D., Keisler, J. M., Seager, T., & Linkov, I. (2017). Resilience and efficiency in transportation networks. *Science Advances, 3*(12), Article e1701079.
Ganin, A. A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J. M., Kott, A., & Linkov, I. (2016). Operational resilience: Concepts, design and analysis. *Scientific Reports, 6*(1), 1–12.
Girod, D. (2015). *Explaining post-conflict reconstruction*. Oxford University Press.
Greenwood, W. W., Lynch, J. P., & Zekkos, D. (2019). Applications of UAVs in civil infrastructure. *Journal of Infrastructure Systems, 25*(2), Article 04019002.
Group of Seven (G7) (2022). Finance ministers and central bank governors meeting communiqué. 18-20 May 2022. Petersburg, Germany. Available online: https://home.treasury.gov/news/press-releases/jy0797.
Guidotti, R., Chmielewski, H., Unnikrishnan, V., Gardoni, P., McAllister, T., & van de Lindt, J. (2016). Modeling the resilience of critical infrastructure: The role of network dependencies. *Sustainable and Resilient Infrastructure, 1*(3–4), 153–168.
Hay, A. H., Karney, B., & Martyn, N. (2019). Reconstructing infrastructure for resilient essential services during and following protracted conflict: A conceptual framework. *International Review of the Red Cross, 101*(912), 1001–1029.
Hijmans, R. (2015). *Second-level administrative divisions, Ukraine, 2015*. UC Berkeley, Museum of Vertebrate Zoology. Available at http://purl.stanford.edu/pp624tm0074.
Hoeffler, A. (1998). Challenges of infrastructure rehabilitation and reconstruction in war-affected economies, African development bank. *Economic Research Papers*. No 48.
Holmgren, A. J., Jenelius, E., & Westin, J. (2007). Evaluating strategies for defending electric power networks against antagonistic attacks. *IEEE Transactions on Power Systems, 22*(1), 76–84.
Hynes, W., Trump, B. D., Kirman, A., Haldane, A., & Linkov, I. (2022). Systemic resilience in economics. *Nature Physics, 18*, 381–384. https://doi.org/10.1038/s41567-022-01581-4
IMPACT (2020). Area based risk assessment popasna raion luhansk oblast, eastern ukraine. Available online: https://www.impact-repository.org/document/impact/3c304bb9/IMPACT_UKR_Popasna_ABRA_UKR1906_Mar2020.pdf.
Imran, M., Elbassuoni, S., Castillo, C., Diaz, F., & Meier, P. (2013). Practical extraction of disaster-relevant information from social media. In *Proceedings of the WWW 2013 Companion - 22nd International Conference on World Wide Web*. Association for Computing Machinery.
International Monetary Fund (2022). IMF strategy for fragile and conflict-affected states (FCS), imf policy paper no. 2022/004, ISBN/ISSN: 9798400201820/2663-3493, Washington, D.C. Available at: https://www.imf.org/en/Publications/Policy-Papers/Issues/2022/03/14/The-IMF-Strategy-for-Fragile-and-Conflict-Affected-States-515129.
Ivanenko, O. (2020). Implementation of risk assessment for critical infrastructure protection with the use of risk matrix. *ScienceRise*, (2), 26–38.
Knoth, C., Slimani, S., Appel, M., & Pebesma, E. (2018). Combining automatic and manual image analysis in a web-mapping application for collaborative conflict damage assessment. *Applied Geography, 97*, 25–34. https://doi.org/10.1016/j.apgeog.2018.05.016
Kottmann, F., Kyriakidis, M., Dang, V. N., & Sansavini, G. (2021). Enhancing infrastructure resilience by using dynamically updated damage estimates in optimal repair planning: The power grid case. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 7*(4), Article 04021048.
Kreimer, A. (1998). *The world bank's experience with post-conflict reconstruction. The international bank for reconstruction and development*. Washington, D.C: The World Bank. ISSN 1011-6984.
Kryvasheyeu, Y., Chen, H., Obradovich, N., Moro, E., Van Hentenryck, P., Fowler, J., et al. (2016). Rapid assessment of disaster damage using social media activity. *Science Advances, 2*(3), Article e1500779.
Kumar, K. (1997). *Rebuilding societies after civil war: Critical roles for international assistance (p. 1)*. Boulder, CO: London: L. Rienner.
Kyprianou, I., Carlucci, S., & Serghides, D. (2022). Urban vulnerability in the EMME region and sustainable development goals: A new conceptual framework. *Sustainable Cities and Society*, Article 103763.
Lagos, T., Moreno, R., Espinosa, A. N., Panteli, M., Sacaan, R., Ordonez, F., & Mancarella, P. (2020). Identifying optimal portfolios of resilient network investments against natural hazards, with applications to earthquakes. *IEEE Transactions on Power Systems, 35*(2), 1411–1421.
Lanaras, C., Bioucas-Dias, J., Galliani, S., Baltsavias, E., & Schindler, K. (2018). Super-resolution of Sentinel-2 images: Learning a globally applicable deep neural network. *ISPRS Journal of Photogrammetry and Remote Sensing, 146*, 305–319.
Levin, N., Ali, S., & Crandall, D. (2018). Utilizing remote sensing and big data to quantify conflict intensity: The Arab Spring as a case study. *Applied Geography, 94*, 1–17.
Li, Y., Dong, Y., Frangopol, D. M., & Gautam, D. (2020). Long-term resilience and loss assessment of highway bridges under multiple natural hazards. *Structure and Infrastructure Engineering, 16*(4), 626–641.
Linkov, I., Keenan, J., & Trump, B. D. (2021). *COVID-19: Systemic risk and resilience*. Amsterdam: Springer.
Linkov, I., Trump, B. D., Trump, J., Pescaroli, G., Mavrodieva, A., & Panda, A. (2022). Stress-test the resilience of critical infrastructure. *Nature, 603*(7902), 578.
Loli, M., Kefalas, G., Dafis, S., Mitoulis, S. A., & Schmidt, F. (2022a). Bridge-specific flood risk assessment of transport networks using GIS and remotely sensed data. *Science of the Total Environment, 850*, Article 157976. https://doi.org/10.1016/j.scitotenv.2022.157976. Vol.
Loli, M., Mitoulis, S. A., Tsatsis, A., Manousakis, J., Kourkoulis, R., & Zekkos, D. (2022b). Flood characterization based on forensic analysis of bridge collapse using UAV reconnaissance and CFD simulations. *Science of the Total Environment, 822*, Article 153661.
Mahoney, E., Golan, M., Kurth, M., Trump, B. D., & Linkov, I. (2022). Resilience-by-design and resilience-by-intervention in supply chains for remote and indigenous communities. *Nature Communications, 13*(1), 1–5.
Markogiannaki, O., Xu, H., Chen, F., Mitoulis, S. A., & Parcharidis, I. (2022). Monitoring of a landmark bridge using SAR interferometry coupled with engineering data and forensics. *International Journal of Remote Sensing, 43*(1), 95–119.
Mattsson, L. G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems–a discussion of recent research. *Transportation Research Part A: Policy and Practice, 81*, 16–34.
Maxwell, D., Stites, E., Robillard, S. C., & Wagner, M. (2017). *Conflict and resilience: A synthesis of feinstein international center work on building resilience and protecting livelihoods in conflict-related crises*. Boston: Feinstein International Center, Tufts University.
Merschman, E., Doustmohammadi, M., Salman, A. M., & Anderson, M. (2020). Post-disaster decision framework for bridge repair prioritization to improve road network resilience. *Transportation Research Record, 2674*(3), 81–92.
Mitoulis, S. A., & Argyroudis, S. A. (2021). Restoration models of flood resilient bridges: Survey data. *Data in Brief.* , Article 107088. https://doi.org/10.1016/j.dib.2021.107088
Mitoulis, S. A., Argyroudis, S. A., Loli, M., & Imam, B. (2021). Restoration models for quantifying flood resilience of bridges. *Engineering Structures, 238*, Article 112180.
Moreno, R., Trakas, D. N., Jamieson, M., Panteli, M., Mancarella, P., Strbac, G., & Hatziargyriou, N. (2022). Microgrids against wildfires: Distributed energy resources enhance system resilience. *IEEE Power and Energy Magazine, 20*(1), 78–89.
National Infrastructure Commission (2020). Anticipate, react, recover: Resilient infrastructure systems. London, UK. https://nic.org.uk/app/uploads/Anticipate-React-Recover-28-May-2020.pdf [accessed on 2 Sept 2022].
Nofal, O. M., & van de Lindt, J. W. (2021). High-resolution flood risk approach to quantify the impact of policy change on flood losses at community-level. *International Journal of Disaster Risk Reduction, 62*, Article 102429.
OECD. (2018). *States of fragility 2018*. Paris: OECD Publishing.
Panteli, M., Trakas, D. N., Mancarella, P., & Hatziargyriou, N. D. (2017). Power systems resilience assessment: Hardening and smart operational enhancement strategies. *Proceedings of the IEEE, 105*(7), 1202–1213.
Rattanachot, W., Wang, Y., Chong, D., & Suwansawas, S. (2015). Adaptation strategies of transport infrastructures to global climate change. *Transport Policy, 41*, 159–166.

Schlör, H., Venghaus, S., & Hake, J. F. (2018). The FEW-Nexus city index–measuring urban resilience. *Applied Energy, 210*, 382–392.
Seneviratne, K., Amaratunga, D., & Haigh, R. (2015). Post conflict housing reconstruction: Exploring the challenges of addressing housing needs in Sri Lanka. *Built Environment Project and Asset Management, 5*(4), 432–445. https://doi.org/10.1108/BEPAM-08-2014-0034
Sharma, N., Tabandeh, A., & Gardoni, P. (2018). Resilience analysis: A mathematical formulation to model resilience of engineering systems. *Sustainable and Resilient Infrastructure, 3*(2), 49–67.
Smith, A. W., Argyroudis, S. A., Winter, M. G., & Mitoulis, S. A. (2021). Economic impact of bridge functionality loss from a resilience perspective: Queensferry Crossing, UK. In *, 174. Proceedings of the institution of civil engineers-bridge engineering* (pp. 254–264).
State Statistics Committee of Ukraine (2022), Ukraine's census, Available online: http://2001.ukrcensus.gov.ua/eng/regions/reg_chrks/ accessed on 30 May 2022.
Sukhodolia, O. (2018). implementation of the concept of critical infrastructure protection in ukraine: Achievements and challenges. *Information & Security: An International Journal, 40*, 107–119.
Tang, E. K., & Hao, H. (2010). Numerical simulation of a cable-stayed bridge response to blast loads, Part I: Model development and response calculations. *Engineering Structures, 32*(10), 3180–3192.
The Economist (2022). Reinventing globalisation, Vol 443, No (9301), 18 June 2022.
Tzifakis, N. (2013). *Post-conflict economic reconstruction. Encyclopedia princetoniensis*. The Princeton Encyclopedia of Self-Determination.
UN News (2022). Global perspective human stories. Ukraine war: $100 billion in infrastructure damage, and counting accessed online 3 May 2022: https://news.un.org/en/story/2022/03/1114022.
Wang, W. L., & van de Lindt, J. W. (2022). Quantifying the effect of improved school and residential building codes for tornadoes in community resilience. *Resilient Cities and Structures, 1*(1), 65–79.
Watkins, G., Mueller, S. U., Meller, H., Ramirez, M. C., Serebrisky, T., & Georgoulias, A. (2017). *Lessons from four decades of infrastructure project-related conflicts in latin america and the caribbean*. Inter-American Development Bank.
Weir, D., McQuillan, D., & Francis, R. A. (2019). Civilian science: The potential of participatory environmental monitoring in areas affected by armed conflicts. *Environmental Monitoring and Assessment, 191*, 61. https://doi.org/10.1007/s10661-019-7773-9
Witmer, F. D. W. (2015). Remote sensing of violent conflict: Eyes from above. *International Journal of Remote Sensing, 36*, 2326–2352. https://doi.org/10.1080/01431161.2015.1035412
WSDOT Bridge Design Manual M 23-50.21 (2022). Chapter 12. quantities, costs, and specifications contents.
Yang, D. Y., & Frangopol, D. M. (2019). Life-cycle management of deteriorating civil infrastructure considering resilience to lifetime hazards: A general approach based on renewal-reward processes. *Reliability Engineering & System Safety, 183*, 197–212.
Yang, Y., Ng, S. T., Xu, F. J., & Skitmore, M. (2018). Towards sustainable and resilient high density cities through better integration of infrastructure networks. *Sustainable Cities and Society, 42*, 407–422.
Zamanifar, M., & Hartmann, T. (2021). Decision attributes for disaster recovery planning of transportation networks; A case study. *Transportation Research Part D: Transport and Environment, 93*, Article 102771.
Zorn, C. R., & Shamseldin, A. Y. (2015). Post-disaster infrastructure restoration: A comparison of events for future planning. *International Journal of Disaster Risk Reduction, 13*, 158–166.