Resilience Framework for Aged Bridges Subjected to Human-Induced Hazard - Case Study in Ukraine

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Resilience Framework for Aged Bridges Subjected to Human-Induced Hazard - Case Study in Ukraine

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Abstract. Bridge structures are key components of transport networks, enabling connections between important centres and regions of countries. Their operability and functionality loss due to long-term deterioration or extreme hazards could cause crucial social and economic impacts. Assessment of bridge resilience against these hazards is needed to predict functionality, optimal management, sustainable development, and decision-making in maintenance and post-conflict restoration measures. Nevertheless, no studies exist to date to optimize resilience metrics for aged bridges subjected to human-induced stressors, considering indirect losses due to disruption of the transport network. This is a capability gap that gave the motivation for this research paper. The study covers functionality-related resilience metrics of damaged bridges, associated with direct losses in terms of repair cost, and socio-economic metrics due to the inoperability of the logistic route. The application of a framework for resilience assessment was illustrated with an example of the case study of the post-conflict restoration of Ukrainian aged bridge structures, which experienced extensive war-induced destruction. This research presents a novel application of resilience framework for assets, subjected to war-induced stressors, considering both direct and indirect losses, and introduces cost and safety-based resilience indexes.

Keywords: Resilience · Bridges · Damages · Deterioration · Post-conflict Recovery · Ukraine

1 Introduction

Bridges play a key role in the performance of infrastructural systems, enabling communication between different regions across any country. In addition to general ageing and deterioration, these structures are often subjected to different natural disasters (earthquakes, floods, tsunamis) and human-induced hazards (e.g. artillery fire during the conflict), which is often the reason for their inappropriate state and limited functionality. The probable bridge failure leads to significant social and economic consequences due to the worsening of logistic routes and the inability of effective post-hazard recovery, which is a common problem in many countries nowadays [1, 2].

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In general, resilience is the system's ability to withstand and recover from a catastrophic event. Its assessment, as defined in [3–5] encompasses dimensions in technical, organizational, social, and economic sectors. System resilience hinges on the following properties: robustness, redundancy, resourcefulness, and rapidity. Robustness signifies the system's capacity to maintain functionality under varying hazard intensities. Redundancy assesses the availability to replace system components if functionality decreases. Resourcefulness refers to the system's ability to quickly respond to external threats and utilize available resources. Rapidity measures how quickly the system regains functionality after a hazard, minimizing downtime [3, 4]. Integrating these parameters resilience metrics are obtained, aiding efficient decision-making for post-disaster recovery.

The resilience assessment, thus, covers three targeted outcomes: low probability of failure, limited probability of critical consequences, and rapid recovery. Recovery planning, prevention of further damage propagation, and optimization of resources' use are vital operations for incentivizing infrastructure recovery and post-conflict rehabilitation in war-torn countries. Resilience quantification for restoring vital bridges should account for both structural and transportation capacity. This involves functionality-based and socio-economic metrics, addressing direct and indirect losses due to disrupted transportation routes. Alternative scenarios for enhancing resilience due to the reduction of indirect losses can be considered with the use of benefit-cost models [6]. Functionality-based resilience (robustness, resourcefulness, redundancy, rapidity), is normally evaluated as a function of the area under the functionality curve $Q(t)$ within the specific timespan. For bridges, being the backbone of the recovery process, socio-economic metrics should additionally be considered. Thus, recent studies [2–4] refer to the cost-based resilience index, which takes into account both direct and indirect losses due to traffic detours and delays.

Failure or damage of bridges has considerable socio-economic consequences for the sustainability of overall transport infrastructure, e.g. environmental footprint, life-quality impact, etc. This highlights the necessity of sustainable restoration strategies placing particular focus on selecting alternative materials, reducing material consumption, and incorporating local or recycled materials. Energy consumption and environmental impact are also critical sustainability metrics, as the recovery of hazard-damaged structures entails additional energy expenditure and increased emissions during restoration [7]. Implementing ongoing hazard-resilient structural designs, considering local conditions, would provide the synergic effect of the potential reduction in social, environmental, and economic impacts from hazard exposure, which is especially relevant for post-conflict recovery in war-torn regions [7]. However, rapid budget assignment and additional initial investment of resources associated with enhanced hazard protection design and sustainable restoration could be challenging in case of post-conflict recovery of the entire region in limited-cost conditions. [7]. Considering all the stated above, the efficient and optimal recovery process of bridges, subjected to multi-hazard environments (e.g. war-induces explosions and general deterioration) requires preliminary evaluation of direct and indirect losses, sustainability and resilience metrics for thorough planning, prioritization and decision-making. Although, previous studies introduced approaches for the assessment of resilience, only a few of them consider indirect losses, associated with the inoperability of transport infrastructure and there is a very limited amount of research on resilience to human-induced stressors (e.g. war, and terrorist attacks). Most existing studies were focused on natural hazards, while the failure of a bridge during the hostilities is a complex issue, requiring consideration of proximity factors and increased downtime due to limited access to assets, which is a novel aspect, covered in this research. In the face of the enhanced risk of terrorist attacks worldwide, a reliable approach for strategic planning and recovery prioritization reaches topicality for any country. This paper fills this gap of knowledge, introducing a resilience framework, which takes into account indirect losses due to inoperability of a logistic route with the use of cost- and safety-based indexes. The proposed framework is of significant practical relevance for regions facing similar hostilities or having a high risk for terrorist attacks, e.g. areas with political and socio-economic instability, ethnic or religious tensions, or active conflict zones. In this study the application of a framework is illustrated with an example of the post-conflict restoration of Ukrainian aged bridges, demonstrating real-world applicability. Ukraine, having 55% of the arable land area is one of the world's top agricultural producers, thus disruption of logistic routes will lead to global negative consequences on both regional and international scales, which makes bridges of Ukraine an effective case study for illustration of the resilience framework.

2 Resilience Framework for Combined Ageing and Human-Induced Hazards

The resilience assessment framework, proposed in international literature [1, 2] was adopted and modified for application for post-conflict recovery (see Fig. 1).

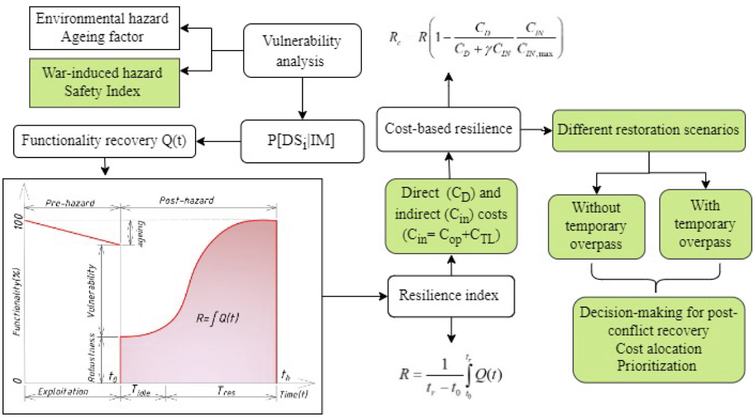


Fig. 1. The flowchart for resilience assessment (novel aspects highlighted with green).

In particular, the unique aspects of human-induced hazards as the proximity to more affected zones and increased downtime were introduced. to multi-hazard environment. Assessment of vulnerability to multi-hazard environment integrates two negative factors: (1) general deterioration due to long-term exploitation and (2) war-induced damages, caused by explosions/ artillery fire. Equation (1) describes the fragility (Frag) of structure as the probability (P) of being in one of the damage states (DS_i, i = [0…4]) for the particular hazard intensity measure of explosion (IM). In this work damage states are defined as intact (DS0), slight damages (DS1), moderate damages (DS2), considerable damages (DS3) and total failure of the bridge (DS4) [2].

$$Frag = P[ds > DS_i|IM], \ i = [0...4] \tag{1}$$

The resilience curve for bridges subjected to explosion can be described by Eq. (2). It is based on restoration functions [2], which indicate the rapidity of functional recovery of the structure from various DSs, considering the probability of its occurrence.

$$Q(t) = \sum_{i=0}^{4} Q[DS_i|t]P[DS_i|IM], \tag{2}$$

where the function $Q[DS_i|t]$ describes the level of functionality of the bridge at t time of restoration from each DS.

Next, the resilience index is determined as the area under the Q(t) normalized by a target time or maximum restoration time (t_r) [2], which is calculated with Eq. (3):

$$R = \frac{1}{t_r - t_0} \int_{t_0}^{t_r} Q(t), \tag{3}$$

where t_0 defines the time point when the explosion occurred and t is a variable, which includes both, the idle time and restoration time.

Resilience index in Eq. (3) is associated with functionality-related resilience metrics due to direct losses caused by damage/ failure of the bridge. However, it is important to consider bridges as important parts of transport infrastructure, the failure of which leads to considerable indirect losses due to limited or impossible operability of communication routes. Thus, socio-economic metrics of resilience can be considered with the use of cost-based resilience index R_c [2, 3]:

$$R_c = R\left(1 - \frac{C_D}{C_D + \gamma C_{IN}} \frac{C_{IN}}{C_{IN,\max}}\right), \tag{4}$$

where C_D defines the direct costs for repair of the bridge, considering the probabilities of damage in different damage states DS_i:

$$C_D = C \cdot W \cdot L \sum_{i=0}^{4} (P[ds = DS_i|IM] \cdot DR_i), \tag{5}$$

where C indicates the repair cost for 1 m^2 of a bridge of similar type, W and L are its width and length, and DR_i is a ratio of repair cost according to the level of damage. The probability of occurrence of particular DS, if a hazard has intensity IM ($P[ds = DS_i|IM]$) is then:

$$P[DS_i|IM] = \begin{cases} P[ds > DS_{i+1}|IM] - P[ds > DS_i|IM] & \text{if i = 1...3} \\ P[ds > DS_i|IM] & \text{if i = 4} \end{cases} \tag{6}$$

In addition to direct costs, the indirect losses due to the necessity of detour include the operating costs of vehicles on a detour (C_{OP}) and the costs due to vehicle time loss (C_{TL}) [2, 8] (see Eqs. (7), (8)).

$$C_{OP} = \sum_{i=1}^{4}\left\{P[ds = DS_i|IM\,]\left(T_{idl,i} + \frac{T_{res,i}}{2}\right)\left[C_{OP,car}\left(1 - \frac{TR_D}{100}\right) + C_{OP,truck}\frac{TR_D}{100}\right]D_l ADT\right\}, \quad (7)$$

$$\cdot C_{TL} = \sum_{i=1}^{4}\left\{\begin{array}{l} P[ds = DS_i|IM\,]\left(T_{idl,i} + \frac{T_{res,i}}{2}\right)\left[\begin{array}{l} C_{AW}O_{car}\left(1 - \frac{TR_D}{100}\right) \\ +\left(C_{ATC}O_{truck} + C_{goods}\right)\frac{TR_D}{100} \end{array}\right]\frac{D_l}{S}ADT \\ +ADE\left(\frac{1}{S_D} - \frac{1}{S_0}\right) \end{array}\right\}, \quad (8)$$

where $T_{idl,i}$, $T_{res,i}$ are idle and restoration time of a bridge from particular DS; $C_{OP,car}$, $C_{OP,truck}$ indicate the average cost of cars and trucks operation; D_l denotes additional length due to detour; ADT and ADE are average daily traffic on the detour and remaining daily traffic on the bridge after the damage occurred; TR_D is a percent of trucks in the daily traffic; C_{AW}, C_{ATC} and C_{goods} define the average wage, total compensation and the cost to transport goods in cargo (per hour); O_{car} and O_{truck} are daily vehicle occupancy for cars and trucks, respectively; S, S_D and S_0 are the average velocity on the detour, on the damaged and intact bridge, respectively [2].

3 Case Study of Post-conflict Recovery in Ukraine

3.1 Portfolio of Bridges

Russian invasion in Ukraine has caused significant damages to Ukrainian infrastructural assets, especially bridges, and it can be expected, that bridges will continue playing a key role until the end of the war, whenever that is, being fought over, defended, and attacked [8–10]. As the “key terrain” in military circumstances, these structures with high probability will be subjected to significant damages or even total failure, due to explosions, artillery fire, shelling, or targeted destruction for strategic purposes.

In addition, it has to be considered, that even before the beginning of the war in Ukraine, their technical state and capability to meet the requirements for carrying capacity and dimensions of today’s roadway were of considerable doubt. According to recent reports from regional authorities [11, 12], about 81% of bridges were built before 1981 and most of the biggest bridges have the age of over 60 years. Thus, it is obvious, that the post-conflict recovery in Ukraine will include the necessary restoration of bridge structures, which requires optimal planning and strategic approach.

For this purpose, the resilience of the 18 biggest bridges in Ukraine was assessed, according to the methodology, described in the previous section. The following Table 1 gives a summary of information about the analysed assets.

3.2 Vulnerability Analysis

In order to assess the vulnerability of bridges, they were ranged, according to relative distance from the front line (autumn, 2023). Thus, assets were grouped according to the probability of war-induced damage and corresponding safety indexes (SI) were

Table 1. Portfolio of 18 biggest bridges in Ukraine.

No	Name	Coordinates	Year of constr. (repair)	L/W (m)	Type*
1	Petrivsky Bridge, Kyiv	50.4837°, 30.548°	1945 (2005)	1430/5	1
2	Darnytsky Bridge I, Kyiv	50.416°, 30.586°	1949	954/15	2
3	Kryukiv Bridge, Kremenchuk	49.053°, 33.424°	1949	1700/8	2
4	Marefa-Kherson Bridge, Dnipro	48.467°, 35.083°	1951	1627/5	3
5	Preobradgensky Bridge I, Zaporizha	47.846°, 35.086°	1952	560/15	3
6	Preobradgensky Bridge II, Zaporizha	47.821°, 35.075°	1952	228/15	3
7	Paton Bridge, Kyiv	50.427°, 30.582°	1953	1543/21	4
8	Antoniv Bridge I, Kherson	46.676°, 32.796°	1954	514/6.7	1
9	Amur Bridge, Dnipro	48.488°, 35.028°	1955 (2002)	1395/15.5	1
10	Southern Bug Bridge, Mykolaiv	46.987°, 31.964°	1964 (2004)	750.7.15.7	5
11	Metro Bridge, Kyiv	50.443°, 30.565°	1965	682.6/28	3
12	Central Bridge, Dnipro	48.477°, 35.057°	1966 (2019)	1478/21	5
13	Northern Bridge, Kyiv	50.491°, 30.536°	1976	816/31.4	6
14	Kaidatsky Bridge, Dnipro	48.501°, 34.968°	1982 (2019)	1732/26	5
15	Antoniv Bridge II, Kherson	46.670°, 32.720°	1985	1366/25	5
16	Southern Bridge, Kyiv	50.395°, 30.589°	1990	1256/41	6
17	Southern Bridge, Dnipro	48.410°, 35.097°	2000	1248/22	5
18	Darnytsky Bridge II, Kyiv	50.416°, 30.586°	2010	1066.2/43.8	2

* Note: 1-truss; 2-combined structure (frame + reinforced concrete (RC) arch); 3-RC arch; 4-steel welded; 5-RC beam; 6-cable stayed

assigned: for bridges in Kyiv (High SI zone)−0.9…1, in Kremenchuk, Dnipro (Medium SI zone)−0.3–0.6, in Zaporizha, Kherson, Mykolaiv (Low SI zone),−0.01–0.2 (proximity based SI). Here as reference served Kherson bridges, which were destroyed [13]. Thus, based on the described above, values of $P[ds > DS_i|IM]$ and $P[DS_i|IM]$ were chosen for each asset (see Table 2). Such a novel approach can be alternatively used for other applications, e.g. terrorist attacks.

To take into account the deterioration of aged bridges, the ageing factor S_{age} was introduced for those, built before 2000 (similarly to [2]), reflecting the reduction of load-bearing capacity by 2.5% for DS1, 5% for DS2, 7.5% for DS3 and 10% for DS4. Although certain restoration measures were made for the most critical assets (see Table 1), they mostly slowed down the process of destruction, rather than fully restoring the capacity of assets. Such minor repair works were considered as a reduction of exploitation time by one decade.

Table 2. Probability of exceedance of DS_i occurrence, considering proximity-based SI

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

3.3 Resilience Analysis

The time required for restoration of each bridge in particular DS was assumed, according to previous works [2, 14] as 90 d/1000 m^2 for full restoration (DS4). For bridges with partial damages, this time duration was reduced by 10% for DS3, by 25% for DS2 and by 75% for DS1, based on engineering judgment.

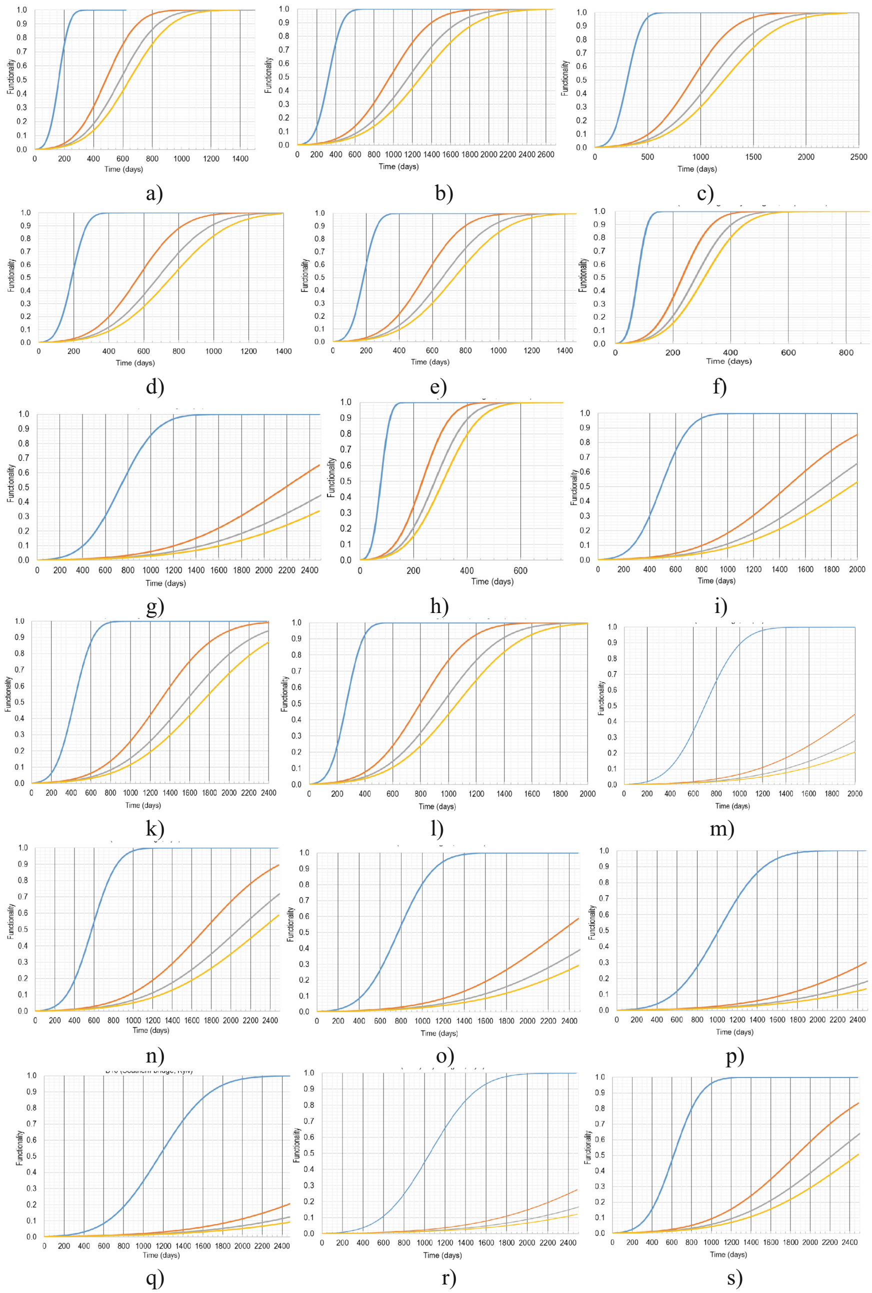
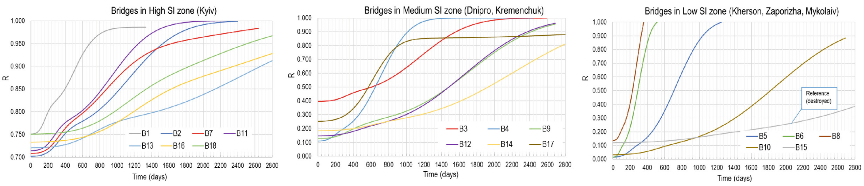


Fig. 2. Restoration curves for bridges B1-B18 (a-s):—-DS1,—-DS2,—-DS3,—-DS4.

Similarly, values for the T_{idl} were taken according to the assumption in [2] as 15 days for DS1, 30, - for DS2, 45, – for DS3, 60, -for DS4 (as higher levels of damage would require more time for preparation of restoration project and allocation of costs for it).

The duration of idle time was further adjusted according to the safety factor to consider the inability to begin restoration works on the territories, close to the front line. As the duration of restoration works is a stochastic value with high uncertainty, the MC simulation was performed to introduce probabilistic model, using a cumulative normal distribution with a standard deviation of 0.35 × mean. Thus, restoration curves were plotted for each bridge in different DSs (see Fig. 2), according to Eq. (2). Similarly, from Eq. (3), resilience curves were obtained and grouped by safety indexes (see Fig. 3).



g) h) i)

Fig. 3. Resilience values for bridges in different SI zones: a) high, b) medium, c) low.

For all the examined bridges the general rapidity of functionality restoration decreases with the increase of damage level (from DS1 to DS4), while the greatest difference can be noted between DS1 and DS2. It should be noted, that as for estimation of the resilience values was based on the MC approach, the probability density function of restoration time was considered, rather than the mean value. Although this assumption is case-specific and provides restoration time much higher, than those in the deterministic approach [2], it more reliably represents uncertainty conditions. Resilience curves in Fig. 3 illustrate functions of achievement of different R values for particular restoration time and ideally should asymptotically reach the full functionality equal to 1. However, although the final restoration time was limited by the same value, for some of the assets the functionality was not 100% restored. As can be seen, resilience values are strongly dependent on the probability of occurrences of DSs, thus the bridges could be grouped according to SI zones. For bridges with the lowest probability of significant damages (High SI), the R values follow a similar trend, while the most rapid resilience increase is for B1 and the slowest, - for B13, which is mostly determined by their area. Similarly, within the bridges in the Medium SI zone, the lowest R values were determined for the bridge with the biggest area (B14) and the sharpest R increase, -for the smallest (B4). Resilience curves for other bridges were equally influenced by the age of assets and the dimensions. In the third group of bridges it was found, that although the starting R value was different for B6 and B8 (different probability of significant damages due to location), their resilience values increased with the higher intensity, compared to B5 and B10 due to smaller dimensions. The lowest resilience was identified for B15, determined equally by the highest probability of failure and big area.

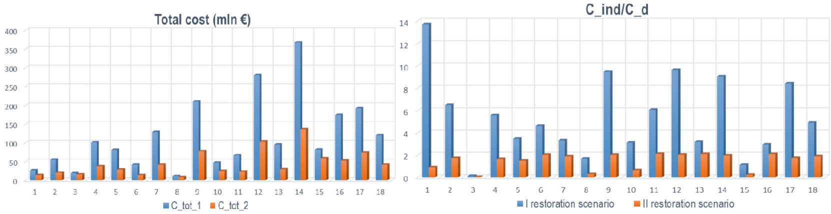
3.4 Cost-Based Resilience

Functionality-based metrics, introduced in the previous section are associated with direct losses and are unchanged during the time. However, disruption of the functionality of bridges results in indirect losses due to the worsening of transport network, which are time-dependent and have to be additionally considered in this case study. Thus, direct and indirect losses were calculated, according to Eq. (5), (7), (8).

Direct costs for restoration of bridge were calculated, considering costs for each bridge type in Ukraine (see Table 1): 1^{st} type-1500 €/m^2, 2^{nd} and 3^{d}-3000 €/m^2, 4^{th} and 6^{th} - 5500 €/m^2, 5^{th} -1400 €/m^2. DR values were assumed as 0, 0.03, 0.08, 0.25 and 0.75 for DS1-DS4, respectively [2].

For calculation of indirect losses $C_{op,car}$ and $C_{op,truck}$ were assumed equal to 0.2 and 0.3 €/km, $TR_D = 20\%$, C_{AW}, C_{ATC} and C_{goods} were equal to 1 €/h, $S_D = 50$ km/h, $S_0 = 90$ km/h, $S = 40$ km/h, $O_{car} = O_{truck} = 2$.

High indirect losses due to timely restoration works initiated the introduction of an alternative restoration scenario with a temporary overpass, which is a novel approach in this study. This enabled the partial operation of transport routes by cars. The cost of the overpass as 4000 €/m was added to direct costs for Scenario 2. Calculated direct and indirect costs are presented in Fig. 4.



a) b)

Fig. 4. Assumed restoration costs (a) and ratio between indirect and direct costs (b) for 2 restoration scenarios.

Cost-based resilience for each bridge was calculated according to Eq. (4) (see Table 3), considering different levels of socio-economic impact of a bridge failure ($\gamma = 0.05\ldots0.15$).

The socio-economic impact of indirect losses is evidently represented by C_{ind}/C_D which shows the consequences of indirect losses for different assets and could be considered as objective measures to facilitate decision-making in recovery prioritisation. Thus, the highest impact of indirect losses was estimated for bridges B1, B9, B12, and B17. However, the introduction of a temporary overpass will enable to partly eliminate these consequences. Although the total costs are lower for the second restoration scenario (see Fig. 4a), it is associated with the fastened allocation of considerable costs required for the construction of temporary overpasses. Also, according to obtained results, the level of socio-economic impact of a bridge failure (γ) has a higher impact on the resilience index for the II restoration scenario, especially for bridges with higher area (e.g. B14, B17, B12, B9), due to longer time of bridge inoperability.

Table 3. Cost-based resilience indexes and direct and indirect losses for 18 bridges.

		I Scenario				II Scenario			
	R	$\frac{C_{ind}}{C_D}$	C_{tot} (mln €)	Rc ($\gamma = 0.05$)	R_c ($\gamma = 0.15$)	$\frac{C_{ind}}{C_D}$	C_{tot} (mln €)	Rc ($\gamma = 0.05$)	R_c ($\gamma = 0.15$)
1	0.985	13.71	26.49	0.988	0.993	0.90	14.25	0.929	0.934
2	0.999	6.49	54.98	0.983	0.992	1.74	20.48	0.867	0.886
3	0.995	0.14	19.04	0.998	0.998	0.04	15.78	0.993	0.993
4	0.997	5.56	101.29	0.979	0.991	1.65	37.64	0.775	0.823
5	0.985	3.45	81.37	0.981	0.992	1.51	28.59	0.829	0.858
6	0.993	4.60	41.72	0.986	0.993	2.02	13.98	0.902	0.913
7	0.988	3.31	128.82	0.978	0.991	1.88	41.31	0.746	0.806
8	0.999	1.68	11.33	0.995	0.996	0.31	8.22	0.979	0.979
9	0.941	9.45	210.11	0.975	0.991	2.02	77.50	0.573	0.717
10	0.859	3.11	47.19	0.985	0.993	0.64	25.04	0.899	0.910
11	1.000	6.07	66.83	0.982	0.992	2.10	23.11	0.843	0.868
12	0.930	9.64	280.54	0.974	0.991	2.03	103.48	0.474	0.677
13	0.847	3.18	95.22	0.980	0.992	2.08	29.23	0.806	0.843
14	0.811	9.03	367.28	0.973	0.990	1.95	136.33	0.375	0.643
15	0.386	1.11	81.89	0.984	0.992	0.25	58.77	0.879	0.894
16	0.928	2.95	173.99	0.977	0.991	2.08	52.48	0.682	0.770
17	0.880	8.44	192.29	0.975	0.991	1.75	73.71	0.604	0.731
18	0.967	4.92	120.25	0.978	0.991	1.89	41.68	0.744	0.804

4 Conclusions

The study presents a novel approach for the assessment of cost-based resilience of aged bridge structures, subjected to human-induced hazards (explosions, shelling, terrorist attacks in conflict areas). The framework was demonstrated with the case study of the 18 biggest bridges in Ukraine, which are the most crucial assets for transportation network functionality. Vulnerability and restoration analysis have shown that the most sensitive to distortion of operability are the bridges with the biggest restoration area due to the longer time, required for restoration and longer loss of functionality of transport route. Thus, indirect losses are the highest for the biggest bridges and assets with longer detour lengths, representing the socio-economic impact of indirect losses. Considering the increase of resilience during the restoration works was noted the strong dependency of the rapidity of functionality restoration on the probability of significant damages and the location of the bridge (the closeness to the conflict areas). Two restoration scenarios were considered associated with different levels of initial funding placement and fundraising rapidity, providing different ratios of indirect and direct losses and speed of functionality restoration. Resilience and sustainability metrics, discussed in the research provide a reliable framework for efficient and sustainable asset management, resource allocation and decision-making during post-conflict recovery.

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