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Financing for disaster and climate resilient infrastructure for a net-zero economic transition - The case of transport infrastructure

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Financing for disaster and climate resilient infrastructure for a net-zero economic transition

The case of transport infrastructure

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ABSTRACT

The crux of the world's built ecosystems is to deliver and maintain infrastructure that is efficient and resilient to climate change and other natural disasters, to underpin economic activity, but also sustainable, so that it is not harmful to the environment. Infrastructure resilience and sustainability can be achieved by design and/or by intervention. The financial impacts of natural and human-induced disasters grow, and as a result national and state finances continue to deplete. Therefore, the burden for risk reduction, resilience and net-zero transition is increasingly transferring from the public to the private sector. However, there is an acknowledged lack of private finance to fill this gap, while international financing bodies prioritise infrastructure interventions over design and preparedness and general resilience-based design. This is a capability gap and as a result the private sector with larger financial resources, such as international companies and financial institutions, are unclear whether or how these resilience building activities are of commercial relevance and direct impact to them. This is simply because traditional cost-benefit analysis, to build the business case for resilience, merely based on return on investment falls short because it doesn't capture the wider environmental, societal, or economic co-benefits. Likewise, local governments fail to adopt resilience plans designed centrally by policymakers, and vice-versa, hazards pertinent only to specific areas of a country, are not always considered by policymakers. This position paper will identify the enablers of and barriers to climate resilient and sustainable infrastructure aiming to quantify the trade-offs and synergies between climate resilience and sustainability in the infrastructure development and adaptation. The paper is focuses on transport infrastructure adaptation considering climate projections and sets a benchmark case study for the bridge stock in Ukraine, including highway and railway assets.

INTRODUCTION

Infrastructure designers and operators aim to deliver infrastructure that is resilient to multiple hazards and changing climate conditions[1], and sustainable, to protect the environment, minimise upfront and running costs, and provide safe and efficient services to society. Nevertheless, available infrastructure design does not directly embed the principles of resilience and sustainability, as these are not quantified in the engineering design and assessment guidelines and codes. There have been different frameworks for incorporating these two principles, which are either harmonious and in some other cases competing each other[2]. As a result, it is challenging to optimise the performance of large-scale infrastructure systems and assets whilst meeting resilience and sustainability requirements. One solution to deliver more resilient infrastructure is to build assets that can withstand more extensive threats and shocks by increasing for example their dimensions and hence making them more robust and with high structural redundancies. In doing so we can minimise damage from natural hazards and generate significant (co)benefits in terms of

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[1] Koks E.E., Rozenberg J., Zorn, C. et al. "A global multi-hazard risk analysis of road and railway infrastructure assets2. Nature Comm 10, 2677 (2019) https://doi.org/10.1038/s41467-019-10442-3

[2] Marchese D., Reynolds E., Bates M.E., Morgan H., Clark S.S., Linkov I. "Resilience and sustainability: Similarities and differences in environmental management applications". Science of the Total Environment, 613, 1275-1283. (2018) https://doi.org/10.1016/j.scitotenv.2017.09.086

lower repair costs and maintenance needs over the life cycle of the asset. But to be resilient, assets not only need to be robust; they also need to be well maintained, which requires a steady flow of resources, and hence well planned and soundly estimated targeted investments[14]. Optimising the resilience of transport assets, such as roads, railways and bridges to climate hazards, considering environmental impacts due to e.g., deterioration, climate-induced accelerated corrosion, whole life carbon emissions, and cost, is a first vital step toward combining the two principles into an integrated framework and metrics[3].

In addition to the economic importance of transport infrastructure, its construction and operation contribute significantly to more than 70% of the world-wide greenhouse gas emissions due to infrastructure[4]. Bridges are one of the most vital components of countries' infrastructure and have a number of positive socio-economic impacts. Yet, a large portion of road assets and more specifically bridges has now by far exceeded the expected lifespan of 50 years, while they are currently structurally deficient. As an approximation, the cost to maintain bridges is 10 times more than the corresponding cost for plain roads. However, these costs depend on the local geographical and environmental conditions, the typology of the transport networks, as well as the development of the country[5]. An analysis of member countries of the Organisation for Economic Co-operation and Development performed for this report suggests that every additional $1 spent on road maintenance saves on average $1.50 in new investments, making better maintenance a very cost-effective option[6].

In the US, 36% of bridges need repair work and their cost is estimated at $125 billion[7]. Approximately 53% of the bridge failures are caused by hydraulic actions, such as floods and scour, a number that is likely to be higher these days due to climate exacerbations[8], while corrosion and general deterioration due to aggressive environmental conditions[9] accelerated the loss of capacity and operability[10]. These values are generally mirrored worldwide as a function of the country's GDP, making infrastructure sustainable development a key concern for achieving 2030 emission targets and net-zero by 2050[11]. For example, it is estimated[12] that the cost to maintain transport infrastructure is about 1.3% of the GDP for low- and middle-income countries for the period 2015-2030, which is similar to the cost for new transport infrastructure. This budget can vary depending on local policies, including the targeted level of infrastructure quality and decarbonization.

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[3] Mitoulis SA, Bompa DV, Argyroudis SA. "Sustainability and resilience trade-offs in post-disaster bridge recovery: floods and climate projections" (2022) https://ssrn.com/abstract=4151393.

[4] Saha D "Low-carbon infrastructure: an essential solution to climate change?" (2018) https://blogs.worldbank.org/ppps/low-carbon-infrastructure-essential-solution-climate-change

[5] CEDR Report on BEXPRAC, Paris: Conference of European Directors of Roads (2010). https://www.tiipublications.ie/downloads/SRM/2-CEDR-Report-on-BEXPRAC-March-2010.pdf

[6] Kornejew M, Rentschler J, Hallegatte S "Well Spent: How Governance Determines the Effectiveness of Infrastructure Investments" (2019) Background paper of[14], World Bank, Washington, DC.

[7] ASCE Report Card History "Report Card for America's Infrastructure" (2021). https://infrastructurereportcard.org/making-the-grade/report-card-history

[8] Mitoulis SA, Domaneschi M, Cimellaro GP, Casas JR "Bridge and transport network resilience–a perspective". In Proceedings of the Institution of Civil Engineers-Bridge Engineering 175, 138-149 (2022) https://doi.org/10.1680/jbren.21.00055

[9] Nasr A, Björnsson I, Honfi D, Larsson Ivanov O, Johansson J, & Kjellström, E. "A review of the potential impacts of climate change on the safety and performance of bridges". Sustainable and Resilient Infrastructure, 6(3-4), 192-212 (2021) https://doi.org/10.1080/23789689.2019.1593003

[10] Morcous G. "Performance prediction of bridge deck systems using Markov chains". Journal of performance of Constructed Facilities, 20(2), 146-155 (2006) https://doi.org/10.1061/(ASCE)0887-3828(2006)20:2(146)

[11] European Commission "The European Green Deal", COM(2019) 640 final. (2019) https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf

[12] Rozenberg J., Fay M. "Beyond the Gap: How Countries Can Afford the Infrastructure They Need While Protecting the Planet". Washington, DC: World Bank (2019).

Destructive events around the world, including natural disasters and human-induced hazards, e.g., conflicts[13] highlighted the significance of transport networks to be resilient and for recovery strategies to incorporate sustainable measures with minimal environmental impact. The more resilient and sustainable new infrastructure developments the more incentives are given to public and private investors for investable infrastructure developments. This is particularly important as currently there are very limited resources to adapt, maintain and increase the capacity and lifespan of our infrastructure. Hence, investment decisions should rely on technical evidence and quantitative resilience and sustainability features.

In this background context, the motivation for this position paper is to quantify the cost of recovery strategies in transport infrastructure from the lenses of resilience and sustainability. This optimisation considered the cost of recovery of bridges in an LMIC (Ukraine) after their deterioration over time, while the quantification of sustainability is performed on the basis of upfront carbon emission estimations, as a result of bridge restoration. The reason for the selection of an LMIC is that generally it is expected that the quality of infrastructure is lower in these countries[14] and hence disruption is more frequent, leading to lower resilience. This case study provides analytics, towards a repository of solid case studies on infrastructure and valuation of sustainable asset development to facilitate decision-making for financing and recommendations suited to LMICs.

METHODOLOGY

The infrastructure performance as a function of the infrastructure age is considered to be in this paper a measure of resilience, while the maintenance cost and the corresponding carbon emissions are adopted as measures of sustainability. These metrics are assessed and compared for the bridge portfolio of an LMIC, using openly available data (OpenStreetMaps) and tools (QGIS), for different time horizons, considering a range of climate projections, which might have negative impact in the infrastructure condition. The methodology adopted in this paper followed the steps shown below as a means to compare different investment restoration strategies:

1) Select the LMIC country of interest, define the scale of analysis and spatial units (e.g. administrative units such as regions) and collect relevant data, e.g. environments, GDP, number of assets.
2) Select representative or critical infrastructure assets from transport systems e.g. bridges, and collect relevant data, e.g. average construction cost for typical structures.
3) Identify a database of bridge inventories in the country (e.g. openly available data such as OpenStreetMaps)
4) Rule out assets that do not comply with a typology of infrastructure assets or they are secondary assets, i.e. remove a number of bridges from the inventory such as footways, or abandoned bridges. Create spatial data layers (e.g. shapefiles) for road and railway bridges.
5) Extract the key parameters from the database, such as number of assets, geometry (average width, length) or material for road and railway bridges and produce statistics such as total deck areas.
6) Classify the assets to different periods of construction using data from the literature and/or engineering judgment, if the age of the assets is unknown.
7) Select maps that describe the environmental conditions in the country of interest. Rank the spatial units of step 1 into a class of environmental conditions.
8) Identify the number of bridges in each spatial unit using the layers of steps 1, 4 and 7. Create statistics, i.e. deck area in each environmental condition and period of construction (see step 6).
9) Assess the performance of bridges as a function of its age and environmental conditions, based on well-established models that relate bridge deterioration pace with environmental conditions.
10) Based on the results of step 9, calculate the remainder capacity and the value loss of bridges.

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[13] Mitoulis SA, Argyroudis SA, Panteli M, Fuggini C, Valkaniotis S, Hynes W, Linkov I. “Conflict resilience framework for critical infrastructure peacebuilding” (2022) https://ssrn.com/abstract=4159965

[14] Hallegatte S, Rentschler J, Rozenberg J “Lifelines: The resilient infrastructure opportunity”. World Bank Publications (2019) http://hdl.handle.net/10986/31805 yes select the country of interest

11) Calculate the cost for the reconstruction of the entire portfolio of assets per region and per environmental condition as identified in step 7 and the statistics of step 8, for a representative construction cost of road and railway bridges.
12) Calculate the carbon emissions (MtCO2e) for the reconstruction works, using data from the literature for typical bridges, for conventional and low emissions solutions (e.g. biofuel, green concrete).
13) Repeat steps 8 to 12 for climate projections, which alter the environmental conditions in step 7.
14) Estimate the number of bridges that can be fully recovered for target periods of times (e.g., 15 years), assuming a certain investment rate, e.g. 1.5‰ of the GDP of the country.
15) Re-assess the performance of the bridge stock and the corresponding carbon emissions, considering the recovery of bridges (step 14).
16) Repeat for different investment rates. Produce analytics and compare the results.

CASE STUDY

The methodology described above was applied to produce analytics in terms of resilience and sustainability metrics that can inform financing for climate resilient infrastructure toward a net-zero economic transition.

Steps 1 to 5:

Ukraine with a GDP of 158 bn Euros in 2022 is selected as a case study area of this paper. Figure 1a shows the administrative boundaries of the 27 regions in Ukraine, which were the spatial units of analysis in this application. From the initial inventory[15] of bridges, a total of 37,260 road bridges and 4,320 railway bridges were recorded in the database. A number of road bridges was removed as they were not falling into typical bridge structures. For example, road bridges that were characterised with a surface made of clay, earth, grass, grass-paver, sand and wood were removed as well as footways, paths and pedestrian bridges. From the stock of bridges only the ones between 10 and 250 m were kept in the inventory. Similarly, railway bridges with lengths spanning from 10 to 250 m were kept in the database to process. This filtering resulted in 24,266 road and 3,829 railway bridges, with total lengths of 857 and 163 km, correspondingly. An average width of 10 and 15 m was considered for road and railway bridges correspondingly, to assess the total areas. This resulted to 8.57 million m^2 of total deck area and an average length of 35.3 m for road bridges. For railway bridges, the total deck area was estimated at 2.45 million m^2, and a total length of 164 km with an average length of 42.7 m. Figure 1b shows the road bridges, whilst Figure 1c shows the railway bridges included in this case study. The cost of road bridges was estimated at 3,000 Euros/m^2, whereas the cost of railway bridges was taken as 3,200 Euros/m^2. On average this cost was estimated to be 22% higher when low carbon solutions were considered[3]. In particular, the tCO2e/m^{2}of a representative bridge restored with conventional materials and methods is 3.33 tCO2e/m^2, whereas the low carbon solution results in 1.57 tCO2e/m^2.

Steps 6 to 13:

Subsequently, the bridges were classified into five categories based on a previous study[16] that provides information with regard to the time of construction of bridges in European countries. Figure 2a shows the distribution of bridges for the periods of construction 1900 to 1945; 1946 to 1965; 1966 to 1980; 1981 to 1990; 1991 to present. In this paper a similar distribution of bridges per period of construction was adopted. To characterise the criticality and pace of deterioration of bridges, the study of Shvidenko et al.[17] was used to rank the 27 regions of Ukraine into an environmental condition category, ranging from extremely dry to very wet (i.e., extremely dry, very dry, dry, fresh, humid, moist, wet, very wet). From the

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[15] The Centre for Humanitarian Data (2022) https://data.humdata.org/dataset/hotosm_ukr_roads

[16] Žnidarič A, Pakrashi V, O'Brien E, O'Connor A “A review of road structure data in six European countries”. Proceedings of the Institution of Civil Engineers-Urban design and planning, 164(4), 225-232 (2011) https://doi.org/10.1680/udap.900054

[17] Shvidenko A, Buksha I, Krakovska S, Lakyda P “Vulnerability of Ukrainian forests to climate change”. Sustainability, 9(7), 1152 (2017) https://doi.org/10.3390/su9071152

maps made available, the number of bridges and the corresponding deck area per region and per environmental condition were calculated. The bridges were classified based on performance prediction with a rating from 1 (critical) to 6 (very good) as a function of bridge age[10]. This model provides the pace of bridge deterioration considering the bridge age based on the year of construction and the environmental categories, i.e. benign (extremely dry, very dry), low (dry, fresh), moderate (humid, moist) and severe (wet, very wet)[18]. Figure 2b shows the different environments and the corresponding deterioration rate. This plot shows that the wetter the environment the faster the pace of deterioration. The remainder capacity of the bridge, which was used to assess the value loss of bridges was based on a previous study by Mitoulis et al.[19].

The change in the environmental conditions due to climate change and hence the impact on bridges was also assessed. Three climate projections scenarios were considered for assessing the bridge performance, with the following periods[17]: (a) 2011 to 2030, (b) 2031 to 2050 and (c) 2081 to 2100. It is noted that there is a gap regarding the environmental conditions between 2051 and 2080 and for this period the projection of period (c) above was applied. The general trend in these projections is that the environment becomes drier and hence less hostile to transport infrastructure, leading to progressively lower deterioration rates. Therefore, the environments in Ukraine seem to lead to a slower pace of corrosion of structural components, reinforcements and prestressing of infrastructure assets and in particular bridges. No other factors apart from general deterioration of bridges were considered in the model, e.g. the potential of other hazards such as flooding or earthquakes that can reduce the structural capacity and functionality of the assets.

To account for the additional bridges constructed after 2022 the trend of additional bridge construction over the last 32 years, i.e. 1990 onwards, was considered to apply in future developments of new bridges. This means that for the projection of bridge numbers in the future an average of approximately 76 road bridges are constructed per year and a total of 12 bridges per year are constructed along railways. Therefore, by 2050 the total number of road bridges would increase from 24,266 to 26,389, whereas in railways the total number will increase from 3,829 to 4,164 leading to an average deck area increase of 8.7%. Based on the same rationale the increase in the area of bridges is approximately 24.4% when comparing the stock of bridges in 2100 against the ones in 2022. The results in terms of reconstruction cost and carbon emissions, along with the results for steps 14 to 16 are described in the next section.

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[18] Morcous G, Lounis Z, Mirza MS "Identification of environmental categories for Markovian deterioration models of bridge decks" Journal of Bridge Engineering, 8(6), 353-361 (2003) https://doi.org/10.1061/(ASCE)1084-0702(2003)8:6(353)

[19] Mitoulis SA, Argyroudis SA, Loli M, Imam B "Restoration models for quantifying flood resilience of bridges". Engineering Structures, 238, (2021) https://doi.org/10.1016/j.engstruct.2021.112180

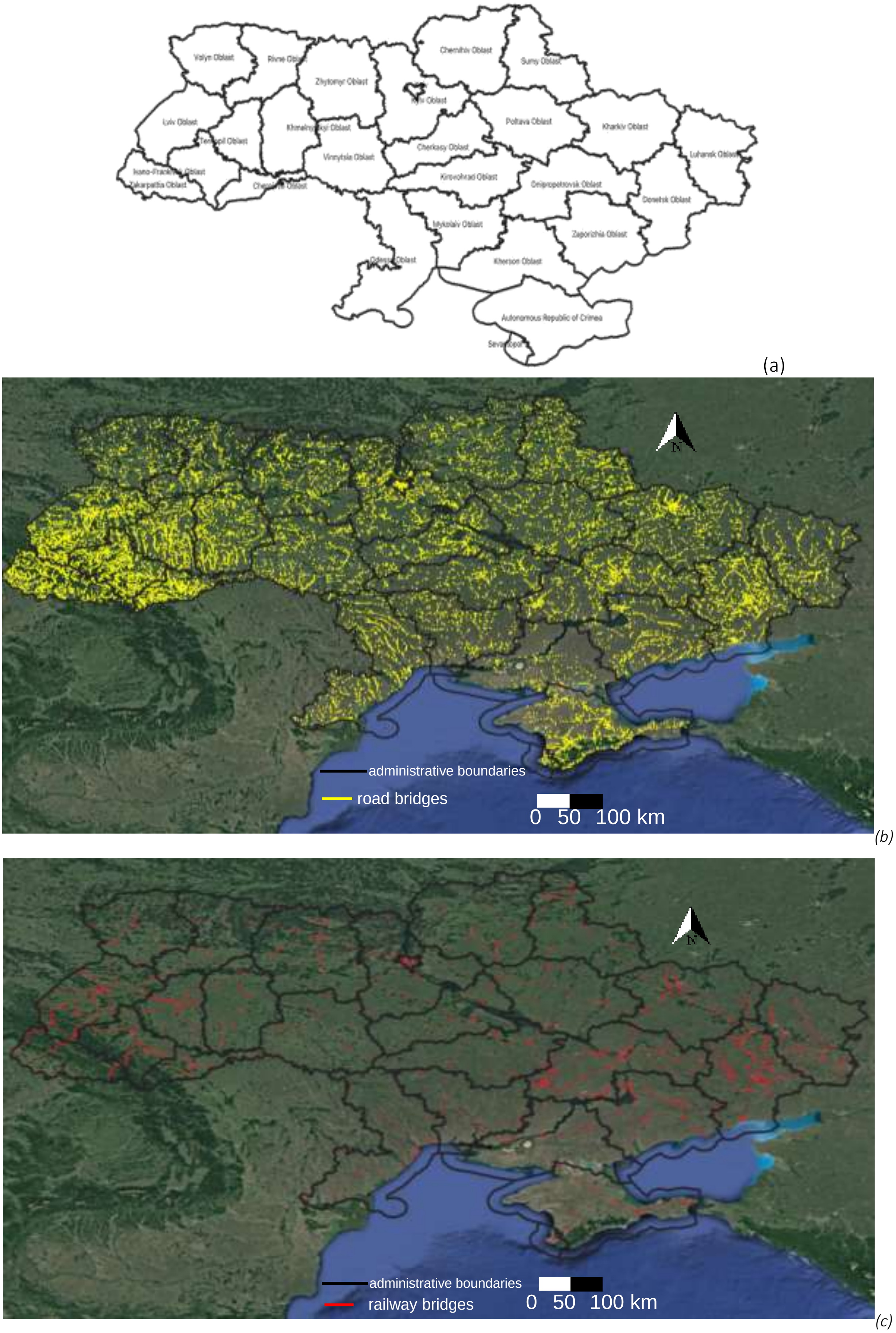


Figure 1: Map of Ukraine with the regions (a), the road (b) and railway (c) bridges of the case study.

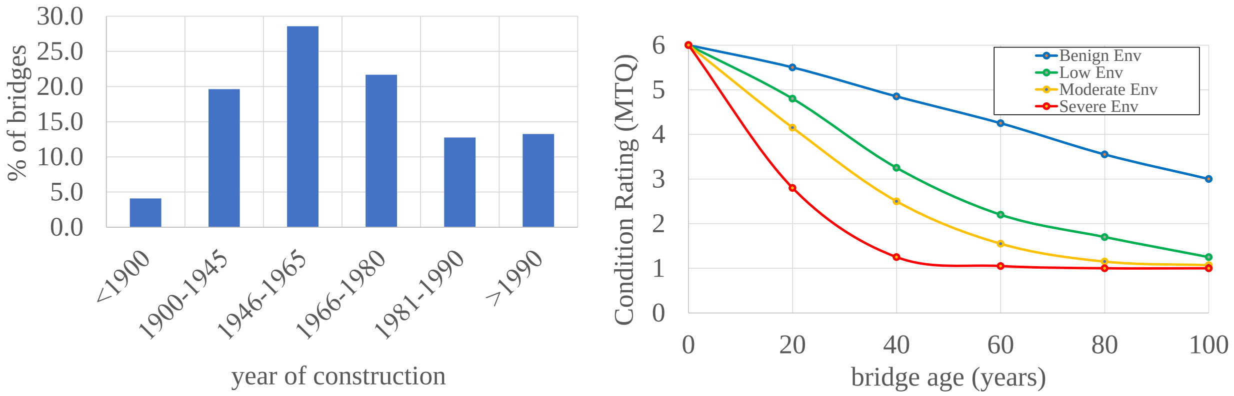
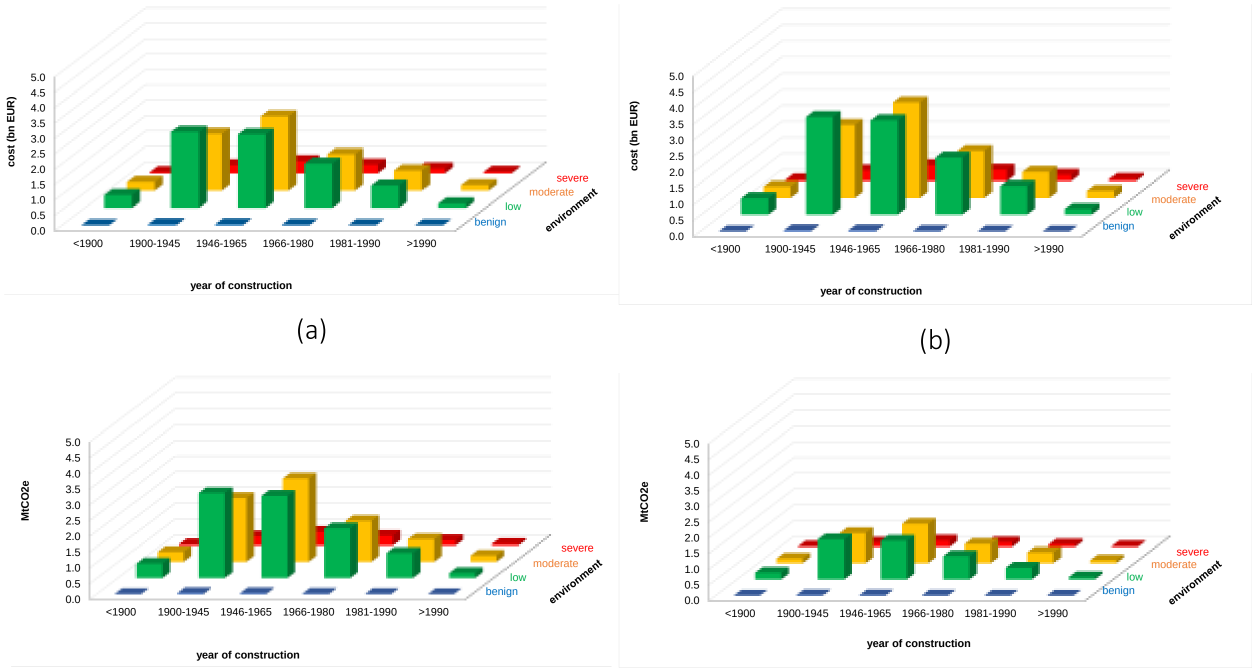


Figure 2: (a) Bridge distribution per period of construction and (b) bridge condition rating based on bridge age.

RESULTS AND DISCUSSION

The main result of the analysis, which was expected, is the fact that on the one hand bridges deteriorate further as time passes and hence the required cumulative investment to compensate for the deterioration process increases, whilst on the other hand the environmental conditions become less severe and as a result bridges become less vulnerable to the environment over time, which leads to less requirement for investment. Figures 3, 4 and 5 show the cost for the restoration of the bridges in the stock in different environments and different ages. The distribution shows the cost in bn Euros for the different years of bridge construction considered in this study. Figure 3a shows the total cost for conventional bridge constructions, whereas Figure 3b shows the cost for sustainable solutions in which cases green materials and less tCO2e intensive methods and fuels were used during the construction process. Figure 3c shows the tCO2e and how these are influenced by the age of the infrastructure assets, whereas Figure 3d shows the tCO2e when more sustainable methods were considered. From this figure it is evident that the main investment should go to bridges at low and moderate environments and bridges constructed between 1900 and 1965 would absorb most of the investment during reconstruction. Currently, greener solutions in bridge restoration lead to higher costs in comparison with the conventional methods, yet the distributions overtime and for different environments of the investment follow the same patterns (see Figures 3c and 3d). The carbon dioxide emissions directly relating to the cost (as more investment for recovery will lead to higher tCO2e) and thus the distributions that we see in Figure 3c and 3d are similar with the conventional methods leading to substantially higher tCO2e in comparison with the ones of the more sustainable methods.

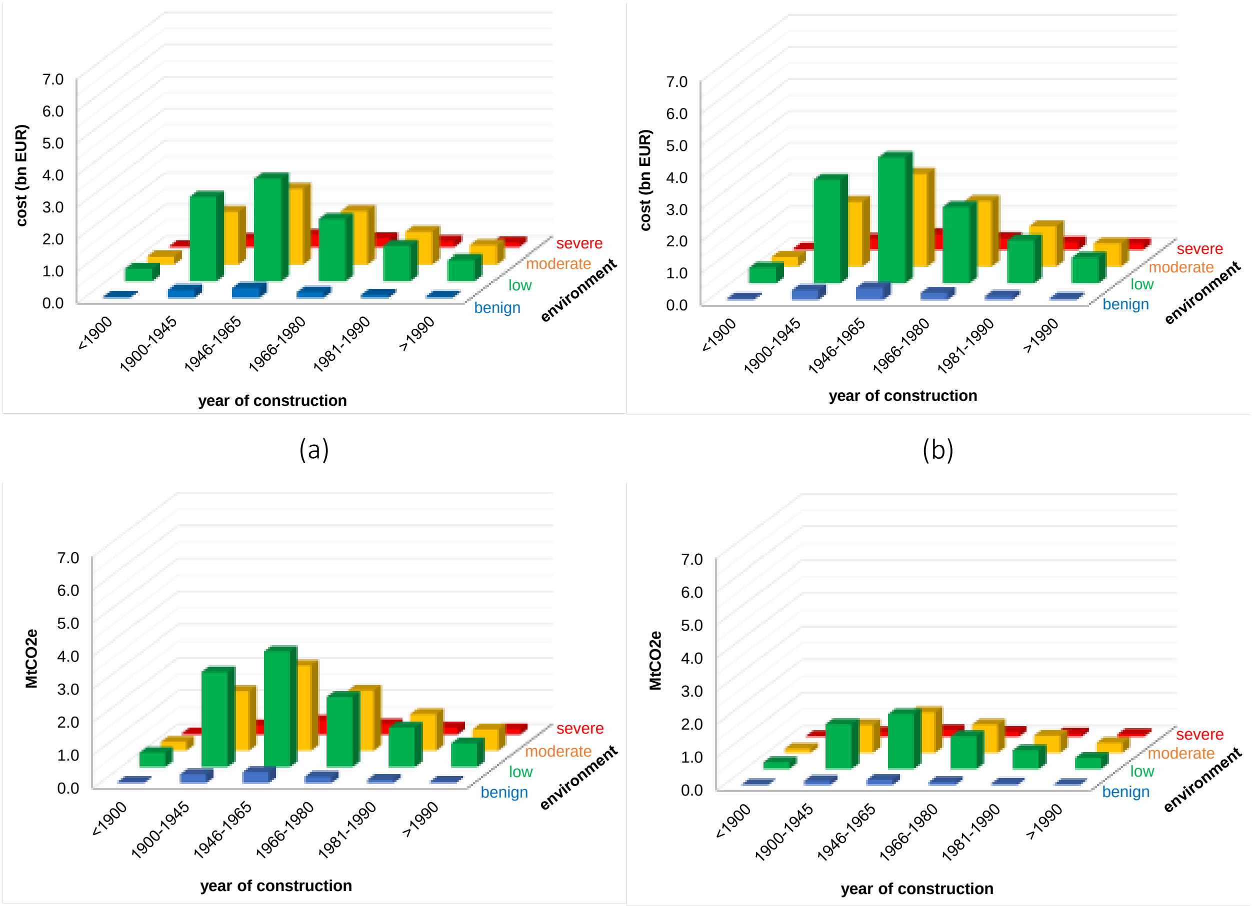
Figures 4 and 5 show the same results, i.e. costs and tCO2e, considering climate projections and correspond to the periods 2031 to 2050 and 2051 and 2100. The main difference between Figure 3 when compared against Figures 4 and 5 is that on one hand the required investment is increased to maintain bridges and critical investment seems to be needed more in low environments rather than on moderate environments. For example, Figure 5 shows the results for the period of assessment 2051 to 2100 in which case most of the investment for bridge reconstruction is needed in areas with low environments as it seems that due to the climate change more areas of Ukraine have transitioned from wet to drier environments. Therefore, a larger number of bridges should be in low environments. This means that many bridges which were considered to reside in moderate environments, for the period of assessment between 2031 in 2050 the same bridges are in low environments due to climate change. Hence, both costs and tCO2e increase for more aggressive environments and whilst the bridge stock is gradually ageing.



(a) (b)

(c) (d)

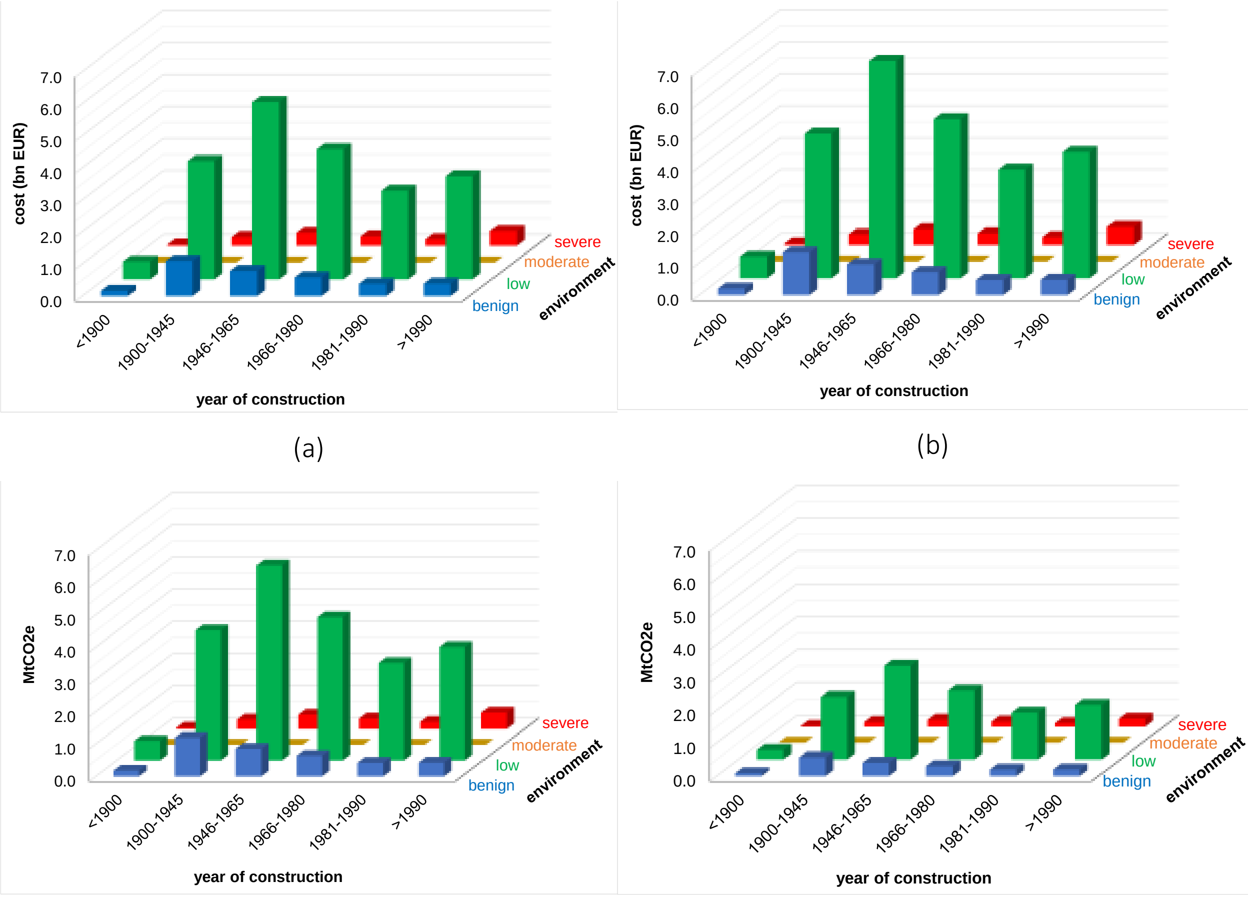
Figure 3: *Period of assessment: 2011-2030*. *The total restoration cost for (a) conventional construction methods and (b) low carbon methods and the total tCO2e for (c) conventional and (b) low carbon.*



(a) (b)

(c) (d)

Figure 4: *Period of assessment: 2031-2050*. *The total restoration cost for (a) conventional construction methods and (b) low carbon methods and the total tCO2e for (c) conventional and (b) low carbon.*



(a)

(b)

(c)

(d)

Figure 5: Period of assessment: 2051-2100. The total restoration cost for (a) conventional construction methods and (b) low carbon methods and the total tCO2e for (c) conventional and (b) low carbon.

On the other hand, the performance rating for bridges as per[10] either reduces or increases overtime depending on whether investment has been allocated for more resilient and more sustainable transport infrastructure. Figure 6a shows the mean bridge performance rating[10] for the stock of bridges that was examined in this paper for four different scenarios: (a) no investment; (b) an investment of 1.32‰ of the GDP of the country (158 bn Euros in 2022), (c) an investment of 1.5x1.32‰ of the GDP and (d) an investment of 2x1.32‰ of the GDP. Based on these scenarios we can see the condition of bridges is declining when no investment is allocated for bridge recovery. However, an investment of 1.32‰ would increase the resilience of the assets as a result of the increase of their performance rating. It seems that with an investment of 1.5x1.32‰ of the GDP, within 78 years from now, i.e. by 2100, the entire bridge stock, including the renewal rate mentioned above, will operate with a mean bridge rating of approximately 6, meaning that bridges are fully meeting their highest performance. In case more investment is allocated for bridge reconstruction, see the case of 2x1.32‰ of the GDP, the resilience of the bridge stock would go beyond the current rating of 6 and this could correspond for example to additional redundancies and capacities of the existing transport network to go beyond the currently assumed best performance level to e.g., adapt to climate changes and other hazards or unforeseen stressors. Figure 6b shows the case of more sustainable construction and recovery of bridges where greater investment is required, at least based on the current prices for sustainable materials toward solutions of lower tCO2e. The gap between these two solutions of Figures 6a and 6b can close by either delivering legislation that will incentivise the use of recycled materials and/or materials of lower tCO2e or by increasing tCO2e taxes to compensate for the additional costs of greener materials. It is recognised that in the future greener materials and more sustainable reconstruction strategies might be competitive or even cheaper than the traditional and conventional recovery methods. It is noted that Figures 6a and 6b consider that the investment goes only to the restoration and refurbishment of bridges, whereas a separate investment is allocated for the development and construction of new bridges.

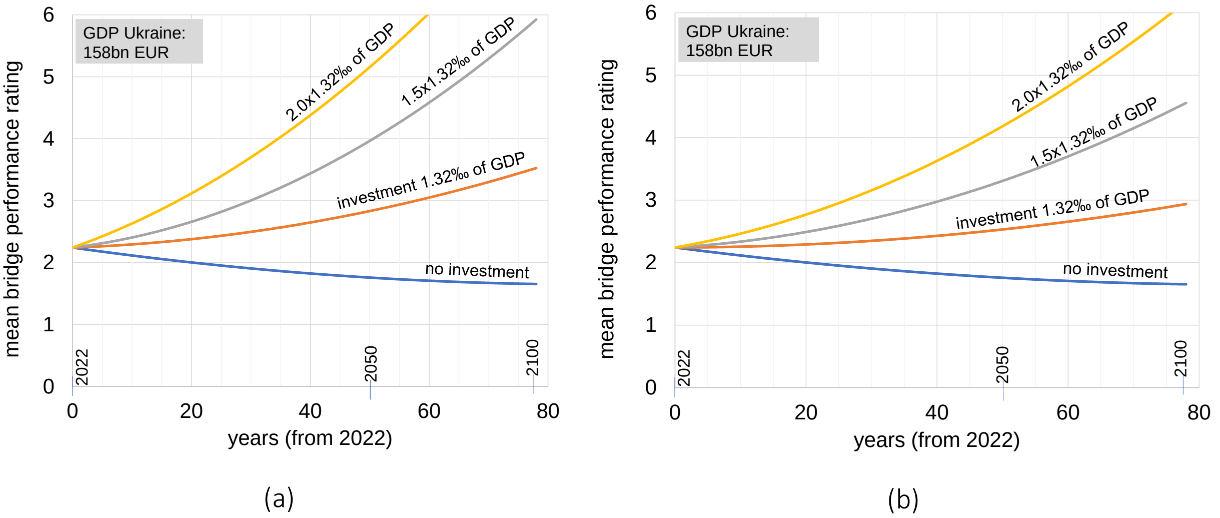


Figure 6: Mean bridge performance rating over the years for different investment strategies for (a) conventional materials and methods of reconstruction and (b) sustainable methods.

To assess all solutions in terms of performance, cost and emissions for three different investment strategies, four environments including the age of the infrastructure and environmental projections in the future until 2100, an indicator was used that weights equally the normalised performance of bridges, the normalised cost, and normalised emissions. It is noted that the performance, cost and emissions were normalised based on the maximum values, i.e. 6 for the performance, while for cost and emissions the maximum values resulted from the case of 2x1.32‰ times the GDP were used. The combined indicator is given by equation 1 below:

$$I_{PCS}=\frac{I_P \cdot I_S}{I_C} \qquad \text{eq. 1}$$

$$I_S = 1/I_{tCO2e} \qquad \text{eq. 2}$$

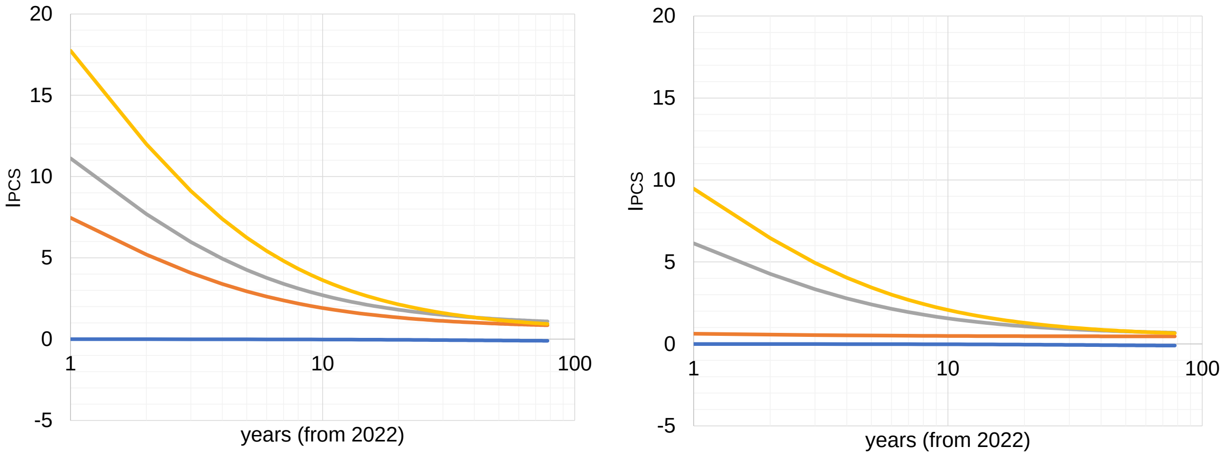
Where I_P is the normalised mean performance indicator for bridges, which is a metric of bridge stock resilience, I_S is the inverse of the I_{tCO2e} (as per eq. 2), an indicator that reflects sustainability, and I_C is the normalised cost indicator of the bridge repair. The maximum values based on which the I_P, I_C and I_S were normalised are given in Table 1:

Table 1. The maximum values based on which the I_P, I_C and I_{tCO2e} were normalised.

Type of bridge recovery solution	max performance[10]	max investment [bn EUR]	max emissions [MtCO2e]
Conventional	6	33.045	35.68
Low carbon/sustainable	6	33.045	16.84

Note 1: Both conventional and low carbon solutions have the same max performance.
Note 2: Investment in this case was considered to be a maximum of 2x1.32‰ times the GDP and identical for conventional and low carbon solutions

Figure 7 shows the rating of the entire bridge stock over a period of 78 years that is from 2022 to 2100. Figure 7a shows the I_{PCS} combined indicator for the four different investment scenarios shown in Figure 6, for the case where conventional bridge recovery measures are being used. Figure 7b shows the same combined indicator I_{PCS} for the case where greener and more sustainable techniques and materials were employed. From these plots, it is evident that despite the fact that the cost and the CO2 emissions increase per year as well as the performance of bridges, it seems that the combined indicator drops with time. The indicator seems to have relatively high values mainly in the first 10 years of investment, an indication that the resilience and sustainability of the stock of bridges increases for a constant investment per year while it is observed that I_{PCS} almost stabilises providing a constant benefit for the same annual investment, thus the increase in the performance is smaller than the increase of cost and CO2 emissions. The second figure shows the evolution of the I_{PCS} factor over time when more sustainable solutions are used, which are currently less competitive due to the relatively higher costs of green materials and processes. Thus, further legislation and incentives are required to establish greener and more sustainable materials and solutions in transport infrastructure development, recovery and reconstruction. These incentives could be for example that the cost of greener materials is not higher than the cost of conventional ones and/or the provision of higher taxes per tCO2e.



(a)

(b)

Figure 7: IPCS rating over the years for different investment strategies for (a) conventional materials and methods of *reconstruction and (b) sustainable methods (colours correspond to the same investments as per Figure 6).*

CONCLUSION

This position paper identified enablers and barriers in climate resilient and sustainable infrastructure development and recovery. The aim of the paper is to quantify the trade-offs and synergies between resilience and sustainable solutions in infrastructure development and adaptation investments. The focus is on transport infrastructure recovery, considering the factors affecting the resilience of critical infrastructure, including natural deterioration of materials and deterioration due to natural hazards through the lifespan of infrastructure. For this case study OpenStreetMaps were used to document the entire bridge stock of a LMIC (Ukraine). The bridge stock was analysed to calculate the cost of recovery to very good condition (highest rating of 6), the evolution of the bridge stock performance improvement over 78 years (until 2100), based on different scenarios of investment ranging from 0 to 2.64‰ of the country's GDP, and weighing in the tCO2e as a result of upfront emissions, i.e., due to materials use only. For the analysis of the bridge stock the condition rating proposed by the literature was used for four different environments. The environments of the country's regions were then matched to literature environments to asset the current and future condition of the assets, accounting for climate projections. Also, the bridges were split into six categories, based on their age measured since the year of construction as per the literature.

The results of the study led to the conclusion that for the case study it is mainly bridges located at moderate and low environments that will require more investment in order to improve the resilience of the infrastructure network, as there are significantly less bridges in severe and benign environments. Total emissions which are the result of bridge recovery and repair follow the same patterns. The bridge environments are expected to change and bridges are expected to deteriorate at a slower pace due to the environmental conditions, because the environment becomes drier and hence the parameters that led to the deterioration of the bridge stock seem to be less severe. As a result, in the future resilience building investment will be directed mainly towards bridges located in low, i.e., drier, environments. Regarding the evolution of bridge performance rating, which is the measure of resilience, the analyses showed that a total of 2.64‰ of the GDP of the country would be adequate to fully restore the resilience of the entire stock of bridges within 78 years, i.e. by 2100. This is true for the case where conventional recovery strategies with traditional materials, methods and techniques are employed, as opposed to low carbon methods. However, considering the higher cost of greener and more sustainable materials, larger investments would be required per year from the country's GDP to fully restore the entire bridge stock.

Regarding the assessment of the entire bridge stock on the basis of (a) performance, as an indicator of resilience, (b) cost as an indicator of investment and (c) emissions as an indicator of sustainability, a complex indicator I_{PCS} was introduced in this paper. This I_{PCS} indicator combines performance cost and sustainability and for this study it introduced the same weights for the three parameters under examination. From the evolution of the I_{PCS} factor for the next 78 years including climate projections, it is evident that the main benefits in terms of performance occurs within the first 5 to 10 years of investment and recovery. During these first years I_{PCS} seems to have the highest values. Further investment after the first 10-20 years, i.e. after 2040, has smaller effect on the I_{PCS}, the values of which seem to converge after this period.

The I_{PCS} was found to be higher for the conventional techniques despite the higher values of the emissions parameter I_S of the more sustainable solutions. This is due to the fact that even though the performance of conventional and sustainable solutions is the same, the cost (I_C) increases with a greater pace in comparison with increase in the I_S and hence reduced emissions of the more sustainable solutions do not offset the increased cost with the current values of the greener solutions. Thus, more incentives are required as a means to support more sustainable refurbishment of bridges and other critical infrastructure. Such incentives could be further legislation in support of greener materials, considering for example maximum costs for green materials that are compatible and/or lower to the conventional ones, and increase in the price of emission taxes, to counterbalance the higher costs of greener solutions.