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Simplified methodology for indirect loss–based prioritization in roadway bridge network risk assessment

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ABSTRACT

Road networks are fundamental for the economic development of regions and play an important role in the day-to-day life of its users. Within the multiple elements of road networks, bridges are among the most vulnerable and recent collapses have increased awareness to both their deteriorated state and overall importance within transportation networks. Direct losses (related to the economic cost of the infrastructure alone) are relatively straightforward to estimate and have been commonly used in risk assessment to date. On the other hand, the indirect component of loss (cost deriving from the reduction in functionality of the road network) is usually neglected, mainly because of the technical challenge it represents and the great amount of information required to perform the road network modelling necessary to calculate these losses to a similar level of detail. This paper presents a detailed methodology to calculate indirect losses and proposes a simplified alternative, which evaluates the relative importance of bridges within a road system in terms of the indirect loss component. For this purpose, the delay that a single user would experience after the collapse of each bridge, when travelling in the network to and from each origin-destination pair, is used as a proxy for the indirect losses in the road network. The simplified alternative uses open-source software and datasets and does not depend on the availability of traffic demands, which can be difficult to obtain. A case study in Salerno, Italy, featuring the principal road network with 617 bridges was used to test both alternatives. The results indicate that the proposed proxy for relative importance of bridges within a given portfolio gives satisfactory estimates when compared to the more extensive calculation. This paves the way for a better and more accessible understanding of the potential impacts of road network interruptions in the overall context of resilience.

1. Introduction

Road transportation networks are a major contributor to the economic development of modern society and play an important role in the everyday life of its users. Whether they are used for transportation of goods, daily commutes of people, or accessibility of emergency services following a disaster, the importance of their proper functionality is undeniable. Modern and developed countries tend to have very dense and robust transportation networks that can include hundreds of thousands of kilometres of roads, typically built over several decades [1,2]. Along with these roads, there is a large amount of supporting infrastructure, such as bridges and viaducts, whose structural integrity is susceptible to natural hazards or general ageing and deterioration. Recent bridge collapses in Italy have demonstrated the large impact that these interruptions can have on the functionality of the surrounding road network for

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extended periods of time. The collapse of the Polcevera (Morandi) bridge, for example, caused indirect losses of €359,1 million in the immediate wake of the collapse, with estimated annual losses to the Italian economy in the vicinity of one billion euros [3]. This has increased public interest in these structures and have thus placed pressure on governments and bridge management agencies to assess and identify vulnerable elements in the network, quantify their fragility to multiple hazards, and determine their respective impact on the overall system. Recent notable efforts led the Italian Superior Council of Public Works, within the Ministry of Infrastructure and Transport (MIT), to issue a technical report with guidelines on risk classification and management, safety assessment and monitoring of existing bridges [4]. These guidelines have already become part of the mandatory legislation for bridge management institutions and concessionaries in Italy [5].

While the probabilistic assessment of a bridge collapse under seismic hazard has been object of research in many past studies [6–8], the direct consequences related to the economic cost of repairing or replacing the structure are usually focused on. The indirect component of loss, which addresses the economic impact incurred when there is a disruption in the road network, remains a less-explored field for researchers and practitioners. Indirect losses have the particularity of being very distributed over a large number of users throughout extended periods of time and many decisions that influence the duration of the interruption are often political and not technical in nature. Also, transportation modelling requires some degree of technical expertise and a large amount of information on both the characteristics of the network and the travel demands of the users, which are not always readily available. Different quantitative approaches have been considered in past research to calculate the effects of infrastructure vulnerability on the performance of transportation systems. Earlier studies aimed to quantify a variety of metrics that can provide insights to the consequences of infrastructure disruption, such as accounting for the loss of connectivity between origin and destination pairs [9], the increase in travel distance [10] or travel delays after the occurrence of disastrous events [11]; these methodologies, however, do not directly account for economic losses. More refined approaches have been proposed, performing a large number of event simulations [12,13]. They account for economic losses in a probabilistic fashion by exploring the effects of events on a transportation network model, even providing estimates of the evolution of the recovery process in time. More recent studies, such as the one performed by Miller and Baker [14], go into great detail by accounting for post-disaster changes in travelling demands and evaluating consequences using activity-based travel models. This permits an analysis that goes beyond economic losses alone, but also the identification of geographic and demographic groups that may be disproportionately affected by certain events. Some more recent efforts [15] evaluate the use of approximate Bayesian networks, trained on results from earthquake simulations influencing an infrastructure system, to predict system performance metrics that can include indirect losses. These studies have the disadvantage of being hazard-specific and requiring a great amount of input data and computational power, which limits their wider applicability to other case studies.

With the above challenges and gaps in mind, this study presents a detailed methodology to calculate the economic impact of interruptions induced in a road network due to the collapse of individual bridges, as well as a simplified alternative to identify the relative importance of the different bridges in a road network portfolio, based on the indirect losses associated to the collapse of each structure. Both alternatives use concepts of transportation network analysis that, in different ways, have been included in the characterisation of indirect losses of bridges in earlier studies. However, the innovation presented herein is centred on the use of such concepts to determine the relative priority of assets in a bridge network, as well as the novel determination of repair times and road network modelling parameters, appropriate for the Italian context. The prioritization of assets is done herein by accounting for the occurrence of collapse, on an exhaustive bridge-by-bridge manner, thus assessing the relative potential disruption effect that the loss of functionality of each bridge would have on the overall network, for an extended period of time. It should be kept in mind that the purpose of the exercise presented herein is not to provide an extensive methodology for the quantification of economic indirect losses, which is complex, as the disruption of a bridge can incur in macro-economic effects that are very difficult to capture in a model. The goal of this study is to provide methodologies that can be useful to identify the relative importance of bridges, in terms of network disruption level, in an inventory for prioritization purposes.

It is also important to note that this study assumes the collapse of a bridge, whenever it reaches any limit state that causes its complete loss of usability and would require its reconstruction. Furthermore, since the methodologies assume the deterministic occurrence of such a limit state, in a bridge-by-bridge manner, independently of the event that caused it, both alternatives are hazard independent. As such, the collapse of multiple bridges simultaneously is not considered herein, since it would require the consideration of specific hazard scenarios to identify the sets of interrupted bridges, which would lead to a significant increase in the complexity of the methodologies and would not be in line with the simplified nature of the current study.

In comparative terms, both the detailed methodology and the simplified alternative share the same basis in road network analysis and require the development of a network model for their implementation. Nonetheless, the simplified alternative is more

Table 1
Comparison between the detailed methodology and its simplified alternative.

Parameter	Detailed methodology	Simplified alternative methodology
Preliminary data requirements	• Road network configuration • Road modelling parameters: number of lanes, volume capacity, free-flow speeds, volume-delay function parameters • Origin-destination travel demands • Expected bridge repair times	• Road network configuration • Road modelling parameters: free-flow speed
Analysis type	Static traffic assignment	Impedance between centroids
Outputs	Economic losses	ΔVHT_i (proxy)

straightforward, relies on less intensive analysis algorithms and is overall less resource demanding than its detailed counterpart, as well as other currently available methodologies that deal with indirect loss characterisation for bridges. A comparison between both presented methodologies, using some key parameters involving the requirements, analysis types and outputs, is presented in Table 1.

2. Methodology

The procedure used in this study to evaluate the proposed indirect loss quantification methodology and its simplified alternative, consists of initially creating the transportation network model for the case-study region (i.e., the province of Salerno, Italy). As can be seen in Fig. 1, two models were considered herein: a refined one, for the detailed methodology, which considers travel demand data and appropriate road modelling parameters to account for congestion in the network; and a less detailed version of the same model, for the simplified alternative, which relies only on information obtained from a common open-source database [16] layer data.

For the detailed methodology, the calculation of the economic impact of bridge interruptions was made using the refined network model to distribute the travel demands in the system. These results were then used to calculate the operation cost of the network's use, combining nominal costs for automobile travel with the aggregated results of time spent and distance travelled daily by the users. This exercise was carried out considering the network in its baseline condition (i.e., when all bridges are operational) and was repeated afterwards by removing each bridge at a time from the model, in order to determine the increased daily operation costs associated with the disruption caused by the absence of each bridge. The total indirect loss associated with each bridge was obtained by multiplying the obtained operation costs by an estimate for the median repair time of bridges in Italy. The full explanation of each of the components mentioned previously, which are required to perform the indirect loss calculation, is presented in Section 4.

On the other hand, given the complexity and amount of information that is required to perform the detailed quantification of economic indirect losses mentioned previously, a simplified approach, aimed towards decision-making purposes, is explored to approximately match the relative importance of bridges in an inventory in terms of indirect loss. This simplified methodology is based on the concept of travel impedance matrices, also referred to as network cost skims, which are a widely-used concept within the transportation planning field [17]. An impedance matrix reflects the inter-zonal travel costs in terms of time, distance or custom cost functions that can be expected in a network. For the simplified methodology defined in the current study, a network skim based on travel time is used to describe the time that a single user would incur to travel each possible combination of centroids as points of departure and arrival in the uncongested network.

For example, an illustrative network with three centroids, along with its respective travel time impedance matrix, is shown in Fig. 2 (a). In this case, each value in the matrix would represent the minimum time that a user would take to travel each combination of centroids. All diagonal elements in the matrix are zero values since intrazonal trips are not considered. Furthermore, the matrix is not symmetrical given that directionality is accounted for, meaning that the route and time required to travel from A to B (AB in the matrix) could be different than its reciprocal travel from B to A (BA in the matrix), depending on the network characteristics. The sum of all the values of the impedance matrix, defined herein as Baseline Vehicle Hours Travelled (BVHT), is used as a metric to evaluate the base conditions of the network when all bridges are operational. Furthermore, the exercise of deriving the skim matrix on the network when a specific bridge has been removed from the model and summing all values to define a Modified Vehicle Hours Travelled (MVHT) can be carried out to evaluate the impact that the absence of that specific bridge will have on the network in comparison to the baseline conditions. An example is shown in Fig. 2(b) where the removal of bridge $\boldsymbol{i}$ leads to increase the impedance of trips between zones B and C.

After repeating the exercise of removing each bridge in the network and calculating its respective time skim, the algebraic difference between the MVHT of each bridge and the BVHT, referred herein as ΔVHT_i, was defined as a proxy value, as shown in Equation (1), which can be used to comparatively evaluate the relative importance of each asset in terms of potential interruption time of the

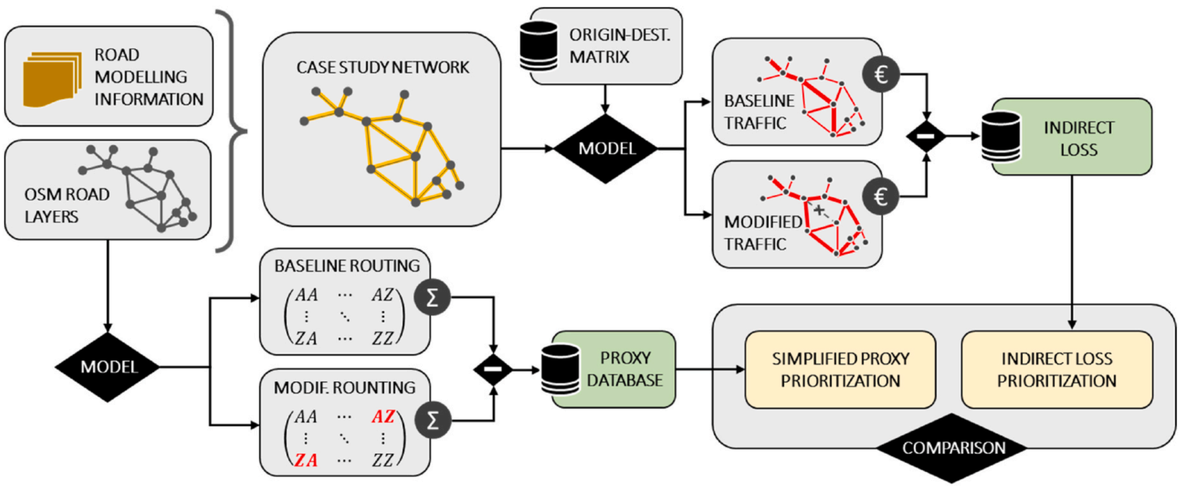


Fig. 1. Methodology used to define a methodology to estimate indirect losses and a simplified proxy-based alternative.

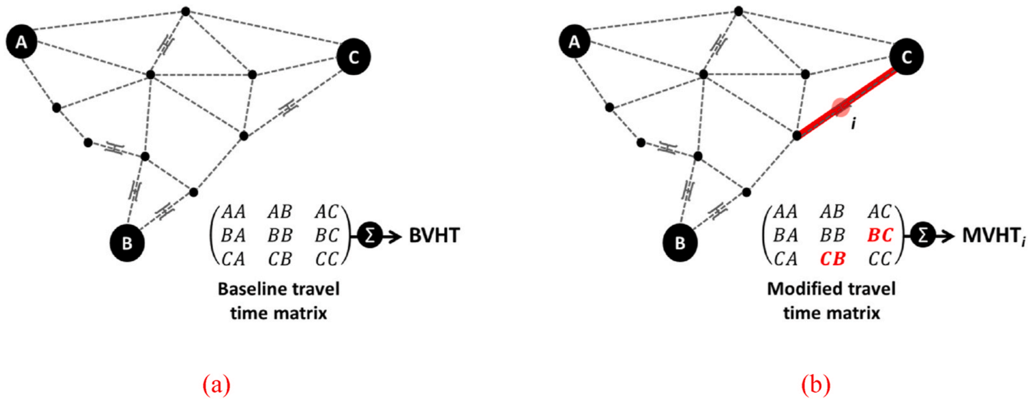


Fig. 2. Definition of proxy value in illustrative network: (a) Determination of baseline travel time with fully functional network, (b) Modified travel times by removing individual bridge.

overall network:

$$\Delta VHT_i = MVHT_i - BVHT \quad \text{(Equation 1)}$$

where BVHT is the sum of all values from travel time skim matrix of the fully operational road network; and $MVHT_i$ is the sum of all values from travel time skim matrix of the road network after removing bridge *i* from the model.

The main advantage of this simplified methodology is that it requires only basic information from the road network that is typically found in open-source repositories with near worldwide coverage, such as OpenStreetMap [16]. Information regarding link properties, used to account for congestion, as well as travel demands between zones, are not necessary since there is no traffic distribution involved, which represents a great benefit, as this information is typically unavailable, incomplete or outdated. Moreover, the determination of the impedance matrices is usually a common output, available in most traffic modelling platforms, whose calculation does not require great computational effort.

Both the detailed methodology and the simplified alternative were applied to 617 bridges located in the highway, primary and secondary road network within the case-study province of Salerno. The results for indirect economic losses calculated using the detailed methodology were used to define the priority of each bridge in the case study, which was then used as a benchmark to evaluate the priorities obtained using the simplified alternative.

3. Case study network

3.1. Salerno road network

The Salerno province was selected as case study for having a transportation network that relies heavily on the vehicular road system and a number of bridges that keeps the current exercise meaningful and more computationally efficient. Information about the road network of Salerno was taken from the OpenStreetMap database [16], which comprises all roads within the highway, primary and

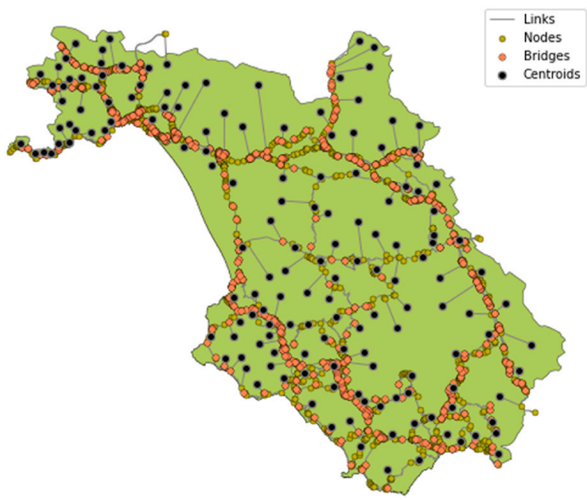


Fig. 3. Salerno road network built from OpenStreetMap layers.

secondary systems, including 2929 nodes and 3086 links, of which 617 represent either bridges, viaducts or overpasses (referred to herein as bridges for simplicity). The geometric centres of the 158 municipalities in the Salerno province were used as traffic attraction zones (centroids) from which all trips were assumed to originate and conclude. A graphical representation of the network is shown in Fig. 3.

3.2. Road network modelling

A transportation network model was created using the software AequilibraE (www.aequilibrae.com), an open-source Python and QGIS package to perform transportation network analysis. Using this, the baseline traffic conditions were determined and the importance of each bridge in the network was assessed. This model is based on Static Traffic Assignment (STA), which is a simple and widely-used assignment method to determine traffic distribution on road networks [18]. The accuracy of this type of model is generally perceived as insufficient in congested networks and the focus of research within the transportation field is shifting towards more refined modelling methods [19]. Nevertheless, STA was chosen herein since it is still the preferred tool for strategic transportation planning due to its simplicity and efficiency [18]. Aside from the geometric configuration of links, nodes and centroids presented in Fig. 3, the following elements were also considered to accurately build a numerical model of the network that can generate predictions on the traffic conditions of the case-study region:

- Traffic demand information regarding the travel patterns of the users of the network between centroids;
- Information about the properties of each link, including free flow speed, nominal traffic capacity and a relationship between traffic flow and travelling speed to account for congestion.

In terms of traffic demands, a database containing travel pattern information for work and study purposes performed in 2011 was taken from the Italian Institute of Statistics [20] and used to define origin-destination demands between the municipalities of Salerno. For the current exercise, only trips performed by private car owners were considered since it represents the major contribution to transportation demands in the area and no information of freight or public transportation was available. A total of 80,562 trips, distributed in four timeframes, were identified within the case study region as shown in Table 2 whereas the daily total incoming trips per municipality are shown in Fig. 4(a).

In terms of link information, all links in the network model were first divided according to their classification (i.e., highway, primary or secondary) in OpenStreetMap as shown in Fig. 4(b). Subsequently, the commonly used volume-delay function defined by the United States' Bureau of Public Roads (BPR) model [21] was used to account for congestion in the network. This function, shown in Equation (2), quantifies the delay in travel time based on the ratio between the vehicle flow and the nominal flow capacity of a road. Its modelling parameters, calibration coefficients α and β, as well as the nominal capacity, were taken from previous research regarding Italian road characteristics [22], according to the different road types defined in the network, as shown in Table 3. Free flow speed was taken as the speed limit reported for each road in the OpenStreetMap database. While some studies [23] modify the speed limit values to try to accurately represent the free flow speed according to the case study characteristics, this was not done in this study since no precedent for acceptable modification factors was found in literature for the case study region. Moreover, the implementation of the speed limit provided good results during the validation stage, which will be demonstrated later in this section. It is important to note that detailed traffic modelling can include additional information on the nodes about intersections, such as accounting for stop-lights and turn penalties, to capture the natural delays caused by drivers making steep angle turns. In the current study, these parameters were not included since they are more relevant for the micro-modelling of urban transportation networks rather than a larger regional assessment; while this represents a limitation of the study, it is not expected that their absence will cause a significant impact on a regional model of motorway and primary roads, such as the one being proposed herein.

$$\frac{\hat{t}}{t_0} = \left(1 + \alpha \cdot \left(\frac{q}{q_{max}}\right)^{\beta}\right) \quad \text{(Equation 2)}$$

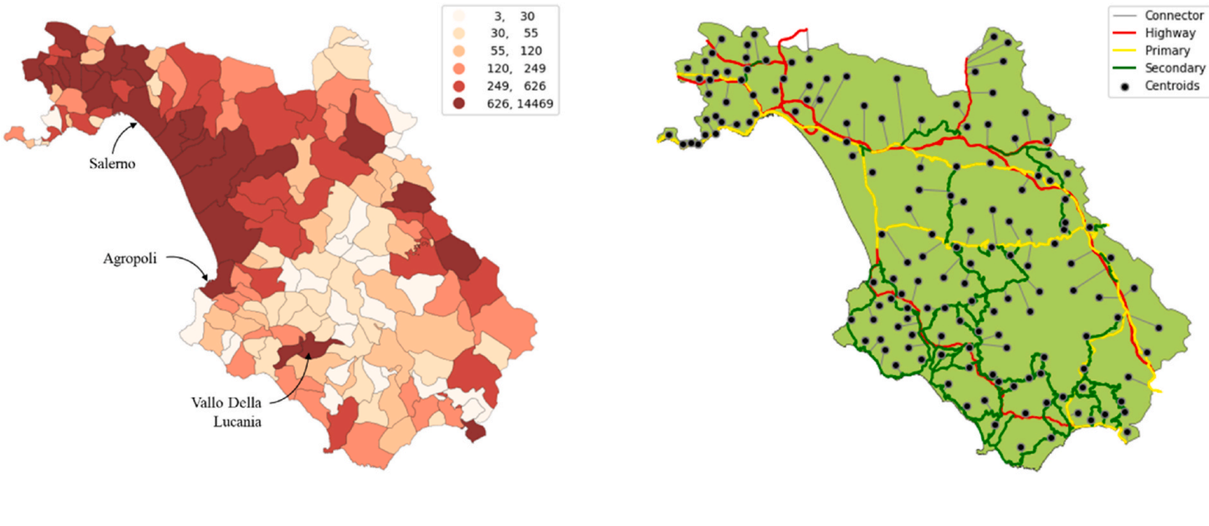
where:

$\hat{t}$: congested travel time.
t_0: free flow time
α, β: calibration coefficients
q: vehicle flow volume
q_{max}: road volume capacity.

A trip distribution based on the minimization of travel time of each user was carried out using a bi-conjugate Frank-Wolfe algorithm

Table 2
Travel demands disaggregated per timeframe taken from census information.

Timeframe	Number of trips
< 07:15	26,138
07:15 – 08:14	38,240
08:15 – 09:14	13,380
> 09:15	2,804
Total	80,562

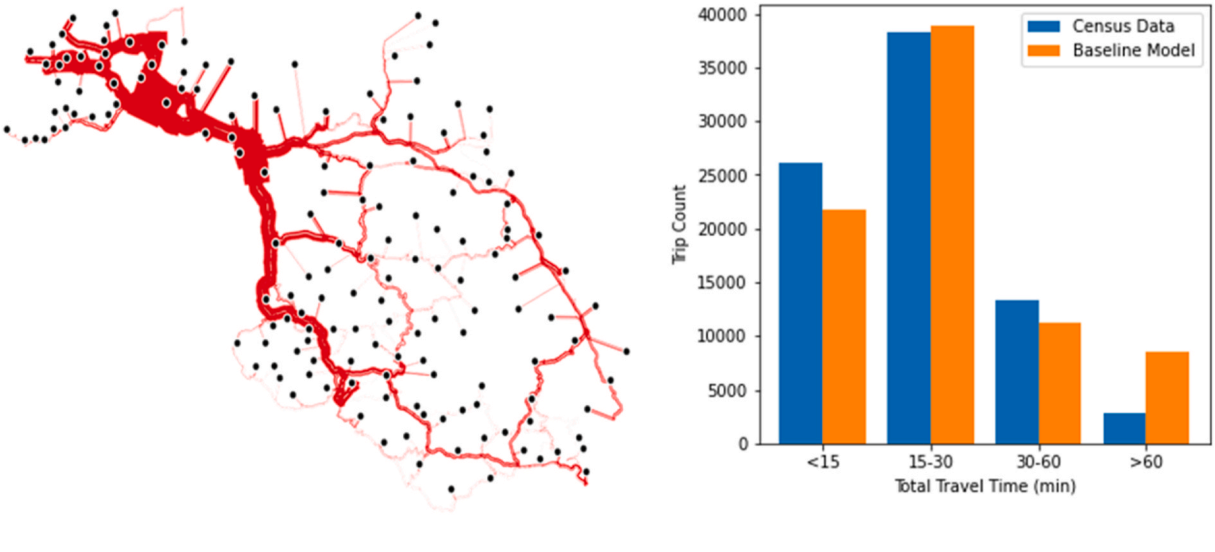


(a) (b)

Fig. 4. Information used to create network model: (a) Daily inbound traffic demands taken from census data, (b) OpenStreetMap road classification.

Table 3
Volume-delay function parameters used for road network modelling.

Typology	Capacity (vehicles/hour/lane)	BPR Parameters	
		α	β
Highway	1600	0.28	0.93
Primary	1400	0.25	1.13
Secondary	1400	0.25	1.13



(a) (b)

Fig. 5. Road network model performance: (a) Baseline traffic flows (line thickness is proportional to traffic flow), (b) Trip duration comparison of census data with baseline model results.

[24] to determine the baseline traffic conditions of the fully operational road network. The results for the distribution in terms of traffic flows for each link, aggregated from each timeframe are shown in Fig. 5(a). It can be seen that there is a large concentration of traffic flows located in the corridor connecting the Salerno and Vallo della Lucania municipalities, which is in agreement with the travel demands shown previously in Fig. 4(a). The results in terms of trip duration were compared with the corresponding values reported in the census data to validate the model. As can be seen in Fig. 5(b), even though the model tends to predict slightly longer travelling times when compared to the census data, overall, there is quite a good general agreement for most of the trips. The mismatch for longer travel times was expected since the model does not include the entirety of roads in the network (i.e., it excludes the local residential road system) therefore increased levels of congestion can occur artificially in the model by having to distribute the totality of the traffic demands in a reduced number of roads.

4. Indirect loss calculation

4.1. Daily indirect loss

To determine the benchmark daily indirect loss associated with the collapse of each bridge in the case study, the previously described road network model, used to determine the baseline conditions of the network when all bridges are operational, was employed. Two main metrics were obtained from the model: the vehicle hours travelled (VHT), and the vehicle distance travelled (VDT), corresponding to the total amount of time and distance, respectively, that all the users in the network experience during their travels. Both metrics were then combined with reference costs for typical automobile fuel efficiency and fuel prices in Italy, as well as hourly salary rates appropriate for the Salerno province [25], as shown in Table 4. This allowed the calculation of a daily operation cost (DOC) of the road network in its current configuration by applying Equation (3).

$$\mathrm{DOC} = F \cdot E \cdot VDT + H \cdot VHT \qquad \text{(Equation 3)}$$

where:

DOC: Daily operation cost.

F: Average cost of fuel.

E: Automobile fuel efficiency.

H: Estimated hourly rate.

VDT: vehicle distance travelled.

VHT: vehicle hours travelled.

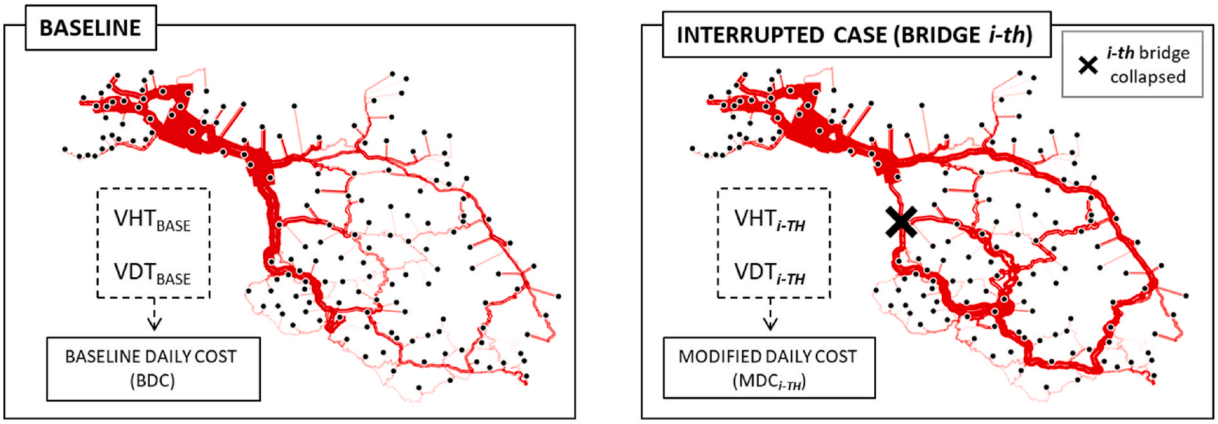
Since the travel demand information that was used only included data from morning commutes, both the VDT and VHT values obtained from the trip distribution on the network were doubled to capture the total daily operation cost of the network. This of course assumes the same travel distribution occurs during the returning evening commute for all users, which might be inaccurate but serves as a reference value within the current methodology. Applying Equation (3) to the results obtained from the trip distribution of the baseline road network model leads to a Baseline Daily Cost (BDC) of operation for the network of approximately €1.64 million. Subsequently, the road network was modified by assuming the collapse of each bridge in the network, removing the appropriate link in the model and rerunning the daily operation cost with the modified network configuration to determine a Modified Daily Cost (MDC), associated with the collapse of each bridge, as shown in Fig. 6. A daily interruption cost of each bridge was then calculated as the difference between the BDC and the appropriate MDC for the bridge in question. Readers are advised to keep in mind that this calculated cost is inherently incomplete, since it does not account for all transportation modes and obviously cannot capture possible losses that the collapse of some bridges would have on local industries, due to increase logistic costs; nonetheless, the calculated costs are proposed herein as reference values of loss for prioritization purposes in a decision-making context.

After conducting this for the entire case study, daily interruption cost results for each bridge were obtained and are shown in Fig. 7. It is important to note that some of the bridges in the case study, identified as essential in Fig. 7, were located near the borders of the case-study region and did not produce interruption cost results when applying this methodology. This was because their collapse resulted in no alternative paths, causing the complete disconnection of some of the centroids. This represents a limitation of the applied methodology since alternate routes are likely available when considering neighbouring parts of the road network, as well as the residential roads that were intentionally excluded from the network model. To avoid this issue in future research, one could either extend the network model beyond the limits of the case-study regions or account for the costs of cancelled trips; however, since in the context of disaster management this disconnection would also deny access to emergency services, the decision made here was to indicate these assets as essential and focus on the remaining 531 bridges that did produce indirect loss results with the methodology used.

Furthermore, a small number of bridges yielded negative values of interruption cost, which would theoretically mean the users are experiencing a monetary benefit from the collapse of a bridge. This is caused by how the distribution algorithm minimises travel time

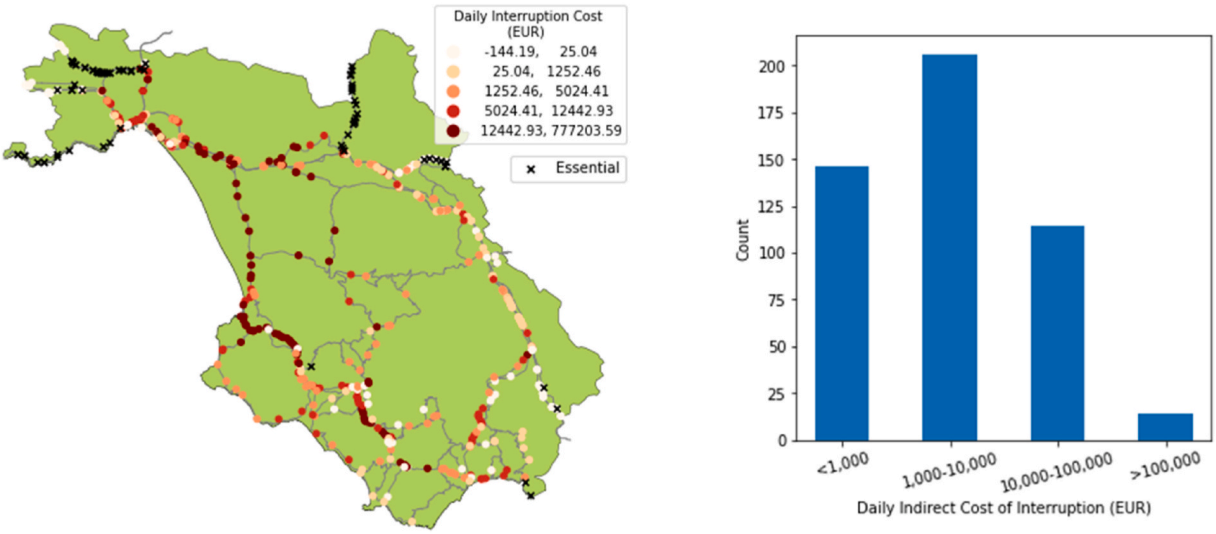
Table 4
Values used for calculation of economic cost of bridge interruption.

Value	Unit Cost
Car efficiency	0.075 L/km
Cost of fuel	€1.65/liter
Average hourly salary (Campania)	€12.9/hour



(a) (b)

Fig. 6. Methodology to determine Daily Indirect Loss: (a) Use of baseline traffic conditions to calculate a daily operational cost, (b) Calculation of modified daily operational cost by removing bridge *i-th*.



(a) (b)

Fig. 7. Daily indirect cost of bridge interruption: (a) Geographical distribution, (b) Histogram.

Table 5
Bridge collapses reported in Italy since 2004.

#	Region	Province	Bridge Name/Location	Length (m)	Collapse Month	Re-opening Month
1	Friuli Venezia Giulia	Pordenone	Viadotto del Chiavalir	25.0	Dec-2004	Jul-2009
2	Liguria	Genova	Carasco	258.0	Oct-2013	Apr-2014
3	Sardinia	Nuoro	Oliena-Dorgali	130.0	Nov-2013	Jan-2020
4	Sicily	Agrigento	Lauricella-Petrulla	476.0	Jul-2014	Mar-2018
5	Lombardy	Lecco	Annone	56.0	Oct-2016	Jul-2019
6	Marche	Ancona	Ancona	45.0	Mar-2017	Jun-2018
7	Liguria	Genova	Viadotto Polcevera	1182.0	Aug-2018	Aug-2020
8	Liguria	Savona	Madonna del Monte	30.0	Nov-2019	Feb-2020
9	Toscana	Massa-Carrara	Albiano Magra	290.0	Apr-2020	Mar-2022
10	Piedmont	Novara	Romagnano Sesia	156.0	Oct-2020	Aug-2021

while the cost calculation also accounts for distance and some longer duration trips might incur in shorter distances therefore causing the overall cost to be negative for a few cases. This is deemed not to be an important limitation since the calculated negative values are negligible for. For example, the bridge with the highest calculated negative value reports a daily indirect loss of -€144, which is distributed amongst the 80,652 users considered in the network, leading to a trivial monetary value in comparison to the highest positive values calculated.

4.2. Repair time

In order to consider the total indirect loss associated to the collapse of a bridge, the total amount of disruption time incurred from the day of the collapse until the reopening of the bridge (referred to herein as repair time) needs to be accounted for. In general, the repair time of bridges varies widely from one case to another, driven mainly by economic and political decisions specific to each case. For example, a non-exhaustive list of bridge collapses in Italy since 2004, collected from reports in the media, is presented in Table 5. It can be seen that, for instance, the collapsed Lecco bridge in 2016 took 33 months to repair and reopen, while the much larger Morandi bridge that collapsed in 2018 took 24 months to reopen, mainly driven by the widespread media coverage of the collapse and relative importance of both bridges to their respective communities.

Previous research on this matter relied on repair time models, for which a probabilistic time is described by some function specific to each country or region, mainly defined through expert opinion. Median repair times used in previous research range from 190 days [12] to 450 days [13]. In this study, the data from the 10 recent collapses in Italy shown in Table 5 was used to fit the lognormal distribution illustrated in Fig. 8.

It is important to note that the median value of 710 days obtained from the lognormal fitting shown in Fig. 8 is much larger than the values used in previous research for other countries, however, the latter values were not based on collapse observations but on expert opinion, and their sources underline the limitations of their definitions [12]. Furthermore, there seems to be a great discrepancy between observed repair times of Italian bridges, ranging from 3 to 75 months for an asset to be reopened after an unexpected collapse. This will obviously have a directly proportional impact on the total indirect loss of a collapsed bridge therefore bridge management agencies should have systems in place to reduce the repair time of assets with high daily disruption costs.

4.3. Total indirect loss results

No evident indication of what repair time from the distribution shown in Fig. 8 can be used for each bridge, hence the median value of 710 days obtained from the lognormal fitting was used as a fixed value for all elements in the case study. This generalization is considered appropriate for the Italian context and is in line with the simplified nature of the current study. However, it is an approximate median based on only ten observations and, therefore, analysts should aim to identify the most suitable value for their own case studies.

Applying this median value as a multiplier to the daily indirect loss results that were previously obtained, enabled the quantification of to the median total indirect loss for each bridge in the case study, as shown in Fig. 9. It is important to note that, instead of using a fixed value of repair time for all the bridges, an extensive sampling scheme could have been adopted by taking different random samples from the distribution shown in Fig. 8 for each bridge in the case study and recording the total indirect loss results for the entire inventory repeatedly. This exercise would, by definition, allow the consideration of expected loss results. However, since this parameter would be the only source of uncertainty considered during the sampling and its effect is linear on the total indirect loss calculation, the sampling exercise would ultimately result in a total indirect loss distribution for the entire inventory with the same distribution as the one for the repair time, with median results equal to the ones reported herein.

The results indicate a median value of total indirect loss of €1.37 million, with 85% of the bridges in the inventory presenting values

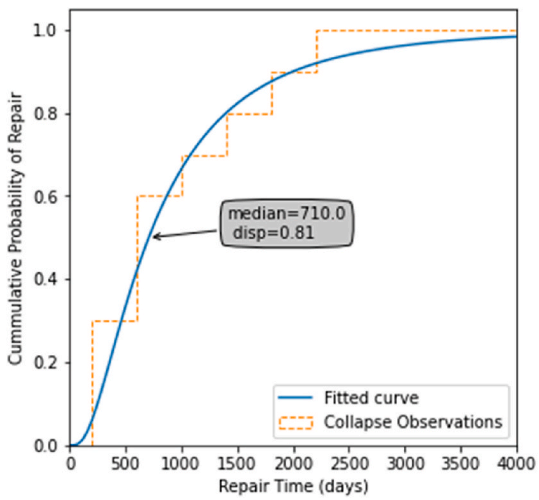


Fig. 8. Empirical cumulative distribution function (eCDF) and lognormal fit for repair time observations based on recent collapses in Italy.

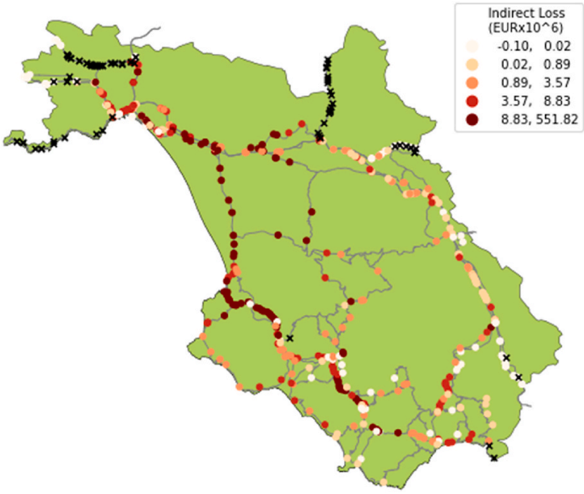


Fig. 9. Results for median total indirect loss on the case-study network.

under €10 million, but with some bridges having very high disruption costs reaching values of €551.82 million. The geographical distribution of the indirect losses seems to closely follow the concentration of traffic flows determined for the baseline condition shown in Fig. 5(a). That is, the bridges with highest losses are located in the corridor connecting the Salerno and Vallo della Lucania municipalities. Moreover, the calculated losses are not necessarily concentrated on highway or primary roads and seem to be greatly influenced by the absence of nearby alternate routes. This confirms that the potential indirect loss associated with the collapse of a bridge is mainly dictated by the baseline traffic demands and redundancy of the network, independently of the road typology where the bridges are located.

5. Case study evaluation

As described in Section 2, the proposed simplified alternative methodology was applied to the case study network in order to compare its performance with the benchmark detailed methodology calculation of indirect losses performed in Section 4. The impedance matrix that represents the travel time of all possible trip combinations between each of the 158 municipalities in the case study was calculated using base conditions of the network, i.e., when all bridges are operational, and then repeated 617 times after removing each bridge in the network, as described previously. For each case, the sum of all values in the impedance matrix was used as a metric that was subtracted from the baseline case to define the ΔVHT_i value described previously. The results obtained for each bridge are shown in Fig. 10.

It can be seen that, qualitatively, the spatial distribution of bridges with higher relative ΔVHT_i values is similar to the one found by the determination of indirect losses shown previously in Fig. 9, where the higher costs of interruption are located in the Western central portion of the case study, near the coast of Salerno. Furthermore, since the same interconnectivity between network nodes is present in all models, the simplified approach also captures the effect of bridges whose collapse results in the complete disconnection of some centroids, therefore being classified as essential.

In order to quantify the comparative performance of the simplified methodology, given that the ΔVHT_i values and the indirect losses cannot be directly compared with each other, for being inherently different, the comparison was made in terms of the priority that is derived by ranking the bridges based on each parameter (higher loss and ΔVHT_i value). Bridges classified as essential were not included in the comparison, since they have no associated numerical results for either parameter. However, their disruption would theoretically cause the complete disconnection of centroids and this should be considered for real application cases. The difference in the ranking positions obtained with the detailed methodology minus the ranking obtained from the simplified methodology is shown in Fig. 11(a). Negative and positive values in this plot represent under and over prediction in priority, respectively, of the simplified alternative, when compared to the detailed methodology. It can be seen that, while the priority rank of some assets can be severely mispredicted by the simplified methodology, the bridges located in the in the corridor connecting the Salerno and Vallo della Lucania municipalities, which presented the highest calculated indirect losses, have rank-difference values close to zero, indicating an accurate prediction of their relative importance in the case-study portfolio. Furthermore, typical regression analysis of both rankings is shown in Fig. 11(b), while the corresponding performance metrics are presented in Table 6, which were calculated by treating the simplified ranking as a regression of the benchmark ranking. It can be seen that using the ΔVHT_i values to determine the priority of assets and comparing it to the one defined by the indirect loss results leads to encouraging results, producing a median absolute error of 61 positions, which represent roughly 12% of the total number of assets in the case study.

Differences between the definition of bridge ranking can be partly attributed to the fact that, when using the detailed methodology to calculate indirect losses, bridges in corridors connecting municipalities with high traffic demands will naturally incur in higher disruption costs and will be therefore prioritized. On the other hand, for the case of the simplified alternative calculation of ΔVHT_i

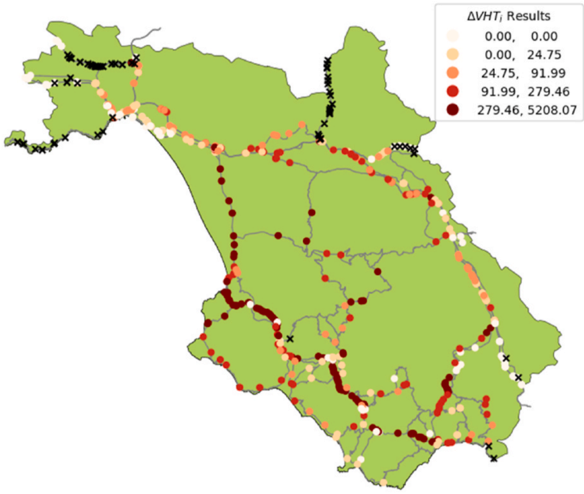


Fig. 10. ΔVHT_i results obtained on the case study application.

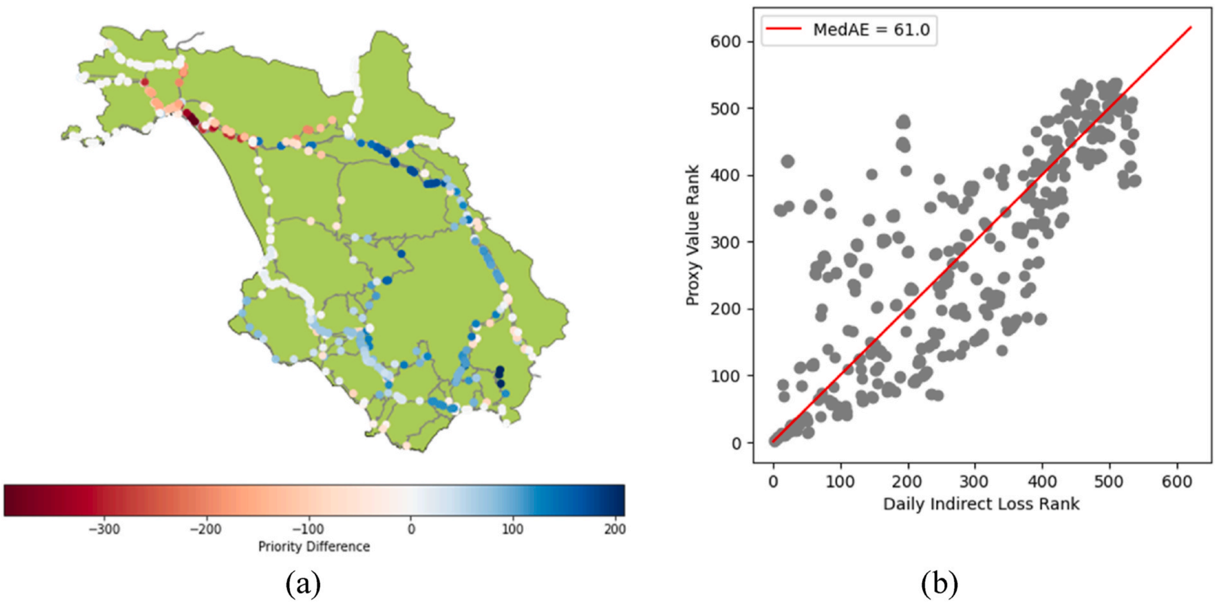


Fig. 11. Comparison of indirect loss and ΔVHT_i -based ranking: (a) Prioritization rank difference (i.e. Indirect Loss-based rank – ΔVHT_i -based rank), (b) Comparison of priorities using both methodologies.

Table 6
Performance metrics for comparison between indirect losses and ΔVHT_i ranking on the case study.

Parameter	Value
Root-mean-squared error (RMSD)	107.9
Mean absolute error (MAE)	79.9
Median absolute error (MedAE)	61.0
Coefficient of determination (R2)	0.505

values, all municipalities have equal relative importance, making it impossible to capture this traffic concentration effect that derives from the user demands. Nonetheless, the performance of the simplified alternative methodology in terms of defining disruption prioritization of bridge inventories represents a good compromise between accuracy, complexity and information demands, in line with the objective of providing an approximate prioritization for decision-making purposes.

6. Summary and conclusions

In this study, a detailed methodology to calculate bridge indirect losses was outlined and tested over a case-study network comprising 617 bridges in the Italian province of Salerno, which were used to create a road network model using open-source software and travel demand data from census information. Such data was used to determine reference values for the daily operational costs of the network in the baseline conditions and when removing each one of the bridges from the model. Information about the time required to restore a bridge was collected from recent Italian collapses to estimate a reasonable disruption duration and determine the total indirect loss of each bridge. Furthermore, as a simplified alternative methodology, aimed for decision-making purposes, the total delay that a single user would experience after removing each bridge from the model, travelling to and from all possible destinations on the uncongested network, referred herein to as $\Delta VHT_{i,}$ was used as a proxy to determine the priority of each asset based on their importance on the road network in terms of indirect losses. Finally, this ΔVHT_i -based ranking was compared to the ranking obtained using the economic values obtained using the detailed methodology to determine its performance. Based on the results obtained via the application of the two methodologies defined, the following conclusions can be drawn:

- The calculation of the economic impact of the disruption in a road network caused by the collapse of a bridge is technically challenging and requires a large amount of information about the properties of the network and the travelling demands of its users. However, it is necessary to quantify the relative importance that bridges have in the network in terms of their functionality, a component that should be included in decision-making strategies by bridge management agencies;
- The detailed methodology presented in this study, to estimate indirect losses associated with the collapse of each bridge in an inventory, has the ability to consistently and efficiently provide reference values of economic loss, which can be used to gauge the impact of the disruption on the road network, caused by a bridge collapsing under any hazard. Nonetheless, the methodology is limited, since it excludes portions of the network and only accounts for a single mode of transportation, therefore, prospective users are advised to keep in mind the applicability of the methodology, which is intended for decision-making purposes;
- Information regarding recent collapses in Italy was used to determine a probabilistic function for repair time of Italian bridges that indicates a median replacement duration of 710 days, which is much larger than the values used in past international research. Furthermore, repair times in Italy vary widely, with past collapsed bridges being replaced anywhere between 3 and 75 months, highlighting the large differences in the way different regions manage their inventories. This parameter has a direct impact in the total indirect losses expected and it is important that bridge management agencies implement procedures so that assets with high daily interruption costs can be replaced faster, thus reducing the overall losses;
- The obtained indirect loss results indicate that these losses are governed by the baseline traffic demands and redundancy of the network, since most of the bridges with higher calculated costs were located in corridors between municipalities with high traffic demands and in portions of the network with fewer alternate routes. This is based on the results obtained from the case-study used in this research and future efforts should focus on evaluating the behaviour of indirect losses on different case-studies;
- As far as the alternative simplified methodology is concerned, it does not provide estimates of economic loss, however, it is significantly easier to deploy for large inventories than previously proposed methodologies. Moreover, it produced prioritization results with an accuracy in the range of approximately ±10% (median absolute error of 61 positions in the ranking order for the case study of 617 bridges), when compared to the ranking based on the detailed calculated indirect losses for each asset. This is considered appropriate for preliminary assessment of bridge importance in a decision-making context.

Declaration of competing interest

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

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