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On supporting traffic management decisions according to bridges structural health monitoring within a digital twin-oriented platform

Mohammad Abbasi[a], Alice Consilvio[a]*, Israel Alejandro Hernández-González[b], Paula Lopez-Arevalo[b], Hamidreza Alavi[c]

[a] *University of Genoa, DIME, Via Montallegro 1, Genoa, 16145, Italy*
[b]*CEMOSA, Calle Benaque 9, Malaga, 29004, Spain*
[c] *University of Cambridge, 7a JJ Thomson Ave, Cambridge CB3 0FA, United Kingdom*

Abstract

The monitoring of highway infrastructures through internet of things sensors allows the storage of high volumes of data. These data can be exploited through artificial intelligence techniques to extract useful information on the assets condition. Operational Modal Analysis (OMA) employing vibration-based techniques stands out among Structural Health Monitoring (SHM) systems, garnering popularity owing to its nondestructive approach, comprehensive damage assessment capacity, and relatively straightforward automation with minimal intrusion. There is a broad literature about structural health monitoring applied to bridges, but its integration within a traffic management system has not received the deserved attention yet. To achieve high performance in terms of network reliability and level of service, the infrastructure manager must make decisions about the traffic flow, considering the percentage of heavy vehicles circulating in the network. The paper presents a decision support model to suggest the best mitigation strategy according to the status of the bridges present in the network and the traffic demand. More in detail, bridge conditions are assessed through a digital twin-oriented platform, the CEMBOX platform, which conducts real-time structural evaluations. According to the degradation level of the bridges, traffic limitation strategies are defined and compared, knowing the transport demand and the traffic composition. The considered mitigation strategies consist of the rerouting of heavy or/and light vehicles, the closure of one or more lanes or the closure of the entire carriageway. The application of the proposed approach to a real-world case study is presented, showing the usefulness of the proposed approach in dealing with bridge and traffic management. The results show that this innovative platform, by providing continuous assessments of bridge integrity, enhances the accuracy of structural health monitoring and the efficiency of traffic management decision support.

* Corresponding author. Tel.: +39 010 335 2530;
E-mail address: alice.consilvio@unige.it

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1. Introduction and literature review

The use of advanced computational tools in civil engineering has brought about a transformation in the approach to infrastructure management, with Building Information Modeling (BIM) and Digital Twin technologies being at the forefront (Consilvio et al., 2023). BIM is a crucial technology that helps manage buildings and infrastructure throughout their lifecycle by creating digital representations (Alavi et al., 2022). Digital Twin technology is an advanced way to interact with infrastructure assets that builds upon the capabilities of BIM (Sacks et al., 2020). It creates a real-time, virtual replica of physical assets that is updated from real-time data, allowing for continuous monitoring and predictive maintenance. Digital Twin technology is a powerful tool that can help manage large-scale infrastructure, such as traffic and Structural Health Monitoring (SHM) systems for bridges. In this regard, digital twins can process and analyze data from sensors installed on bridges, facilitating immediate assessments and predictive maintenance (Zhang and Alipour, 2020)

SHM has emerged as a critical tool for assessing the integrity and safety of bridges. By employing various sensing technologies, SHM provides valuable data that can be used to detect early signs of deterioration or damage. Vibration-based techniques, particularly through Operational Modal Analysis (OMA), have gained prominence due to their non-invasive nature and ability to provide real-time feedback on the structural conditions of bridges (Yang and Frangopol, 2020). OMA is a method utilized in SHM systems to identify the dynamic characteristics of structures under normal operational conditions. It works by using ambient vibration data, which means there is no need for external excitation and the data acquisition process is simplified. OMA is particularly useful for ongoing monitoring of bridges within a digital twin framework, as it can detect changes in modal parameters that may indicate potential damage. This makes it an invaluable tool for ensuring the safety and longevity of bridges (Dan et al., 2022; Khan et al., 2016).

The integration of SHM systems and Digital Twins for traffic management demonstrates how these technologies can predict structural issues and proactively influence traffic management decisions to enhance safety and efficiency (Zhao et al., 2022). This integration can optimize network usage and enhance safety by defining traffic management strategies based on structural health data, mitigating accident risks (Yan et al., 2023; Zhao et al., 2022). This paper aims to explore the utilization of OMA within digital twin platforms to support traffic management decisions by assessing the condition of bridges in real-time.

2. Bridges structural health monitoring

CEMBOX is CEMOSA's in-house digital twin-oriented platform dedicated to SHM. This platform integrates all essential tools for unsupervised damage detection, including signal processing, automated OMA, modal tracking, data normalization, and novelty analysis. The workflow for the continuous assessment of the bridge structure using the CEMBOX platform is outlined in Fig.1. The process involves calibrating the finite element model based on the Structural Identification (St-Id), considering the geometry, materials, and boundary conditions. The process involves iteratively collecting experimental data from the physical asset, performing St-Id through inverse calibration of the Structural Digital Twin (S-DT), and identifying potential damage. To achieve quasi-real-time damage identification, it is crucial to ensure that the total computational time for signal processing, inverse calibration of the S-DT, and damage assessment is less than the acquisition time. This entire process involves four consecutive steps:

(A) Automated OMA – Ambient vibrations are periodically recorded by a data acquisition system (DAQ) and stored in separate data files containing a certain time duration. These acceleration data files are then introduced into CEMBOX platform, where of modal signatures (resonant frequencies f_j, mode shapes ϕ_j, and damping ratios ζ_j) are extracted through automated OMA. The CEMBOX Platform offers two identification tools: Enhanced Frequency Domain Decomposition (EFDD) and Covariance-driven Stochastic Subspace Identification (CoV-SSI), based on frequency and time domains, respectively.

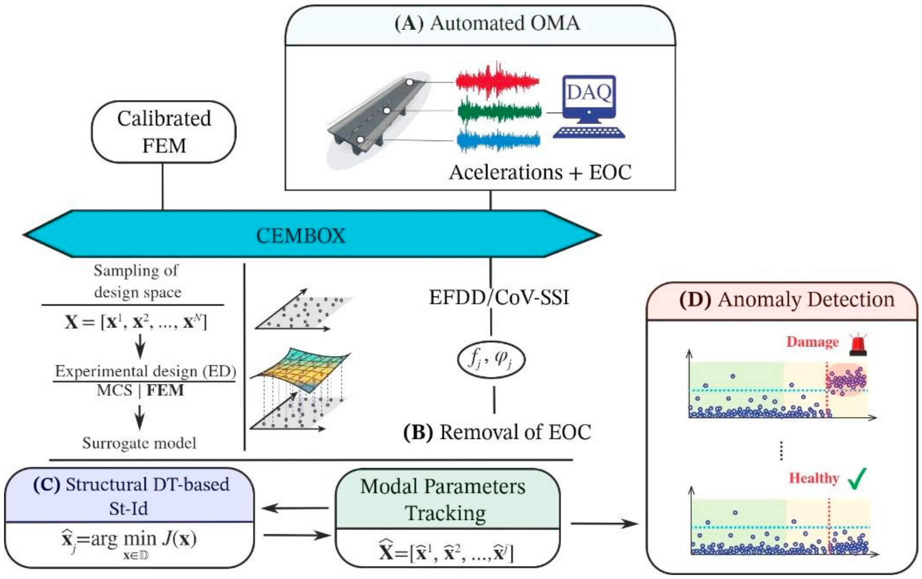

Fig. 1. Flowchart illustrating the application of DT-based continuous St-Id for bridges within the CEMBOX platform.

(B) Removal of EOC – Statistical pattern recognition is employed to minimize the impact of benign fluctuations resulting from Environmental Operational Changes (EOC) on previously identified modal signatures. Data normalization aims to eliminate reversible variability in the selected features induced by benign EOC. This procedure involves training a specific statistical model using samples from a defined baseline in-control population, typically spanning a one-year period to adequately represent the healthy condition of the structure under various EOC scenarios.

(C) S-DT-based St-Id – This phase establishes the St-Id of the asset by updating the S-DT model. It evaluates the disparity between the model's theoretical predictions and the experimentally identified modal signatures. Consequently, specific model parameters ($\hat{\boldsymbol{x}}$) sensitive to damage are adjusted and compiled in an observation matrix, denoted as $\widehat{\mathbf{X}}$.

(D) Anomaly Detection – Finally, the emergence of structural damage can be evaluated through a novelty analysis of the time series encompassing modal signatures and model parameters within $\widehat{\mathbf{X}}$. As these parameters are associated with specific structural elements or damage mechanisms, detecting persistent changes in their time series offers a direct means to assess the location and severity of the damage.

3. Traffic management problem description

In this paper, the information on bridge condition is used to support the infrastructure manager in making decisions about the traffic management in a highway network. It is assumed that the main bridges in the network are monitored through sensors and the collected real-time data are elaborated through the CEMBOX platform to estimate their status.

Traffic management relies on the bridge's state as input, provided by OMA through inverse calibration of the surrogate model. This process determines stiffness values across different parts of the structure. Consequently, degradation level is assessed using the stiffness loss ratio, calculated as the expected modulus of elasticity divided by the actual modulus of elasticity, always yielding a value less than or equal to 1.

Based on this ratio, three levels of degradation are defined: Damage 1 (ratio below 0.95) indicates critical degradation requiring immediate attention, potential traffic restrictions, or structural repairs; Damage 2 (ratio between 0.95 and 0.98) signifies moderate degradation necessitating closer monitoring and possible maintenance; Damage 3 (ratio between 0.98 and 1.0) indicates minimal degradation where the bridge remains in good condition.

In case of high level of degradation, the considered traffic management decisions are the closure of one or more lanes or the closure of the entire carriageway. These types of closures can be imposed for all the vehicles or just for heavy vehicles, which have the greatest impact on bridge structure with their dynamic load.

The developed Mixed Integer Linear Programming (MILP) model is able to define the optimal traffic flow distribution in a highway network represented by a graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ where $\mathcal{N}$ is the set of nodes and $\mathcal{L}$ is the set of links. According to the degradation levels estimated by the OMA, degradation costs are assigned to the links that present bridges.

It is assumed that the infrastructure manager can suggest to the road users the best path to choose and inform them in advance about the closed links. In addition, the infrastructure manager can influence the user behavior, for example by imposing disincentives according to the degradation level of the bridges in the network.

3.1 Mathematical modelling

The following assumptions are considered:

- The considered vehicle types are heavy and light vehicles.
- The origin destination matrices for light and heavy vehicles are known.
- All the links are directed and capacitated. If a link is closed its capacity is set equal to zero. If a lane is closed, the link capacity is reduced.
- If a link is closed just for heavy vehicles, the flow of that type of vehicles is imposed equal to zero on that link.
- The set of links is divided into two subsets: $\mathcal{L}_M$ the set of highway roads links and $\mathcal{L}_L$ the set of local roads links with different capacity and costs. If the local roads cannot be used as alternative path, their capacity is set equal to zero.
- A degradation cost is assumed for links in which at least a degraded bridge is present. It is set to zero for links without degraded bridges. The cost depends on the degradation level of the bridge.

Table 1. Notation of the problem

SETS	
$\mathcal{N}$	Complete set of nodes
$\mathcal{P}$	Set of the origin-destination pairs: $\mathcal{P} = \{(o,d), o \in \mathcal{N}, d \in \mathcal{N},\ o \neq d\}$
$\mathcal{L}_M$	Set of highway roads links
$\mathcal{L}_L$	Set of local roads links
$\mathcal{L}$	Complete set of links: $\mathcal{L} = \mathcal{L}_M \cup \mathcal{L}_L$
$\mathcal{V}$	Set of vehicle types
$\mathcal{G} = \{\mathcal{N}, \mathcal{L}\}$	Graph representing the considered road network
$BS(n)$	Backward Star of node $n \in \mathcal{N}$
$FS(n)$	Forward Star of node $n \in \mathcal{N}$
CONSTANTS	
D_v^k	Origin/Destination (o/d) matrix of the day $k \in \mathcal{T}$ and vehicle type $v \in \mathcal{V}$
$b_{(o,d,v)}^k$	Entry of the matrix D^k referring to the pair $(o,d) \in \mathcal{P}$ and vehicle type $v \in \mathcal{V}$
$\eta_{(n,m)}$	Generalized cost of link $(n,m) \in \mathcal{L}$
$DGC_{(n,m),v}$	Degradation cost the bridge in link $(n,m) \in \mathcal{L}$ and vehicle type $v \in \mathcal{V}$
$q_{(n,m)}$	Capacity of the link $(n,m) \in \mathcal{L}$
β_j	Weight of the objective function j-th term, chosen according to the infrastructure manager intentions
VARIABLES	
$h_{(n,m),(o,d),v}^k$	Path flow on the link $(n,m) \in \mathcal{L}$ for the pair $(o,d) \in \mathcal{P}$, in day k and vehicle type $v \in \mathcal{V}$
$f_{(n,m),v}^k$	Flow on the link $(n,m) \in \mathcal{L}$ in day $k \in \mathcal{T}$ and vehicle type $v \in \mathcal{V}$
$C_{(n,m),v}^k$	Congestion cost of the link $(n,m) \in \mathcal{L}$ in day $k \in \mathcal{T}$ and vehicle type $v \in \mathcal{V}$

The formulation of the proposed model $\forall$ day $k \in \mathcal{T}$, is given by Eq. (1-8).

$$\min \Big(\beta_1 \sum_{(n,m)\in\mathcal{L}_L} \sum_{v\in\mathcal{V}} \eta_{(n,m)} f^k_{(n,m),v} + \beta_2 \sum_{(n,m)\in\mathcal{L}_M} \sum_{v\in\mathcal{V}} \eta_{(n,m)} f^k_{(n,m),v} + \beta_3 \sum_{(n,m)\in\mathcal{L}} \sum_{v\in\mathcal{V}} DGC_{(n,m),v} f^k_{(n,m),v} + \beta_4 \sum_{(n,m)\in\mathcal{L}} \sum_{v\in\mathcal{V}} C^k_{(n,m),v} \Big) \tag{1}$$

subject to:

$$\sum_{m\in FS(n)} h^k_{(n,m),(o,d),v} - \sum_{m\in BS(n)} h^k_{(m,n),(o,d),v} = b^k_{(o,d),v} \qquad \forall n \in \mathcal{N}, \forall v \in \mathcal{V}, \forall (o,d) \in \mathcal{P}: o = n \tag{2}$$

$$\sum_{m\in FS(n)} h^k_{(n,m),(o,d),v} - \sum_{m\in BS(n)} h^k_{(m,n),(o,d),v} = b^k_{(o,d),v} \qquad \forall n \in \mathcal{N}, \forall v \in \mathcal{V}, \forall (o,d) \in \mathcal{P}: d = n \tag{3}$$

$$\sum_{m\in FS(n)} h^k_{(n,m),(o,d),v} - \sum_{m\in BS(n)} h^k_{(m,n),(o,d),v} = 0 \qquad \forall n \in \mathcal{N}, \forall v \in \mathcal{V}, \forall (o,d) \in \mathcal{P}: o, d \neq n \tag{4}$$

$$f^k_{(n,m),v} = \sum_{(o,d)\in\mathcal{P}} h^k_{(n,m),(o,d),v} \qquad \forall (n,m) \in \mathcal{L}, \forall v \in \mathcal{V} \tag{5}$$

$$\sum_{v\in\mathcal{V}} f^k_{(n,m),v} \leq 1.2\, q_{(n,m)} \qquad \forall (n,m) \in \mathcal{L} \tag{6}$$

$$C^k_{(n,m),v} = \max\Big(0, \sum_{v\in\mathcal{V}} f^k_{(n,m),v} - q_{(n,m)}\Big) \qquad \forall (n,m) \in \mathcal{L} \tag{7}$$

$$f^k_{(n,m),v} \geq 0 \qquad \forall (n,m) \in \mathcal{L}, \forall\, v \in \mathcal{V} \tag{8}$$

where:

- the objective function in (1) minimise:
    - the generalised cost on highway links;
    - the generalised cost on local road links;
    - the cost of using links with degraded bridges;
    - the congestion cost.
- the constraints in (2), (3), and (4) represent the flow conservation equations for each node n in case it coincides with the origin, with the destination, or in case it is none of the two, respectively;
- the constraints in (5) represent the link flow;
- the constraints in (6) represent the flow capacity constraints;
- the constraints in (7) define the congestion cost;
- the constraints in (8) guarantee that the flow cannot assume negative values.

4. Case study

To evaluate its performance, the proposed approach is applied to a stretch from a major highway in Italy. The optimization model is solved by using a standard solver of optimization problems (IBM-Ilog Cplex® version 22.11) on a 2.30 GHz processor with 16 GB RAM.

The studied stretch belongs to one of the busiest highways which connects several large cities in Italy and presents a length of approximately 70 kilometers. It experiences heavy traffic, especially during peak-demand periods and holiday seasons. Along this path the highway is split in two parts, the old stretch and the new part. The latter was built in recent years to satisfy an increasing traffic demand. These two parts merge and split in multiple points and present common and exclusive toll gates. It consists of multiple lanes in each direction, typically ranging from 2 to 3 lanes.

The old part passes through diverse landscapes and offers scenic views. This makes it a popular route for both domestic users and tourists. In addition, several local roads are present between the old and the new parts.

The studied road network is represented in Fig.2. The links depicted with black dashed arrows represent the highway sections with two lanes, the links represented with black solid arrows represent the highway sections with three lanes, the blue dashed links represent the local roads. The nodes can represent highway toll points or route decision (merging/diverging) points.

As shown in Fig.2, the degraded bridges are marked with colored stars. Three different levels of degradation are considered, depicted in yellow, orange, and red colors, which correspond to different costs for the users for using those links. The red star shows the most significant level of degradation.

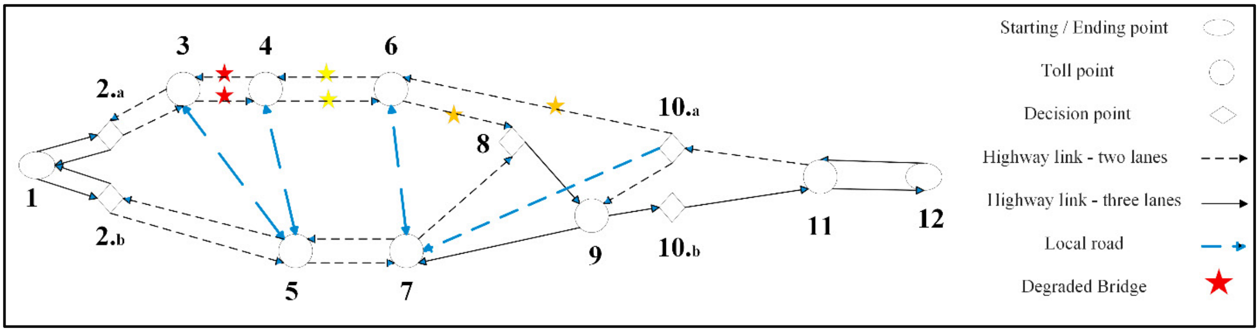

Fig. 2. The studied highway network

For confidentiality reasons, only anonymised realistic data are used. Moreover, the weights of the terms in the objective function (β_j) are assigned based on the knowledge and experience of infrastructure managers. Considering the position of degraded bridges and the presence of local roads in the graph depicted in Fig.2, the following scenarios are defined:

- Scenario 0: nominal situation with no mitigation measures for high degraded bridges.
- Scenario 1: closure of the links with the high degraded bridges (links with red stars in Fig.2) for both light and heavy vehicles with available local roads.
- Scenario 2: closure of the links with the high degraded bridges just for heavy vehicles with available local roads.
- Scenario 3: closure of the links with the high degraded bridges just for heavy vehicles with local roads unavailable for heavy vehicles due to structural and geometrical limitations.
- Scenario 4: reduction of capacity due to lane closure in the link with high degraded bridges with available local roads.

5. Results

In this section, the results from the bridge OMA and the optimisation model for traffic management are reported.

5.1 Standard Bridge Performance Evaluation Results

The dynamic identification approach has been implemented in the CEMBOX platform, CEMOSA in house digital twin-oriented platform dedicated to long-term SHM. The software code integrates essential tools for unsupervised damage detection, including signal processing, automated OMA, modal tracking, data normalization, and novelty analysis. Acceleration records undergo a filtering sequence: elimination of linear trends, removal of anomalous spikes using Hanning window filtering, and application of a second-order high-pass Butterworth filter. The resulting cleansed acceleration time signals are then used to extract modal signatures of a standard bridge using automated EFDD. From these results, the fundamental modal characteristics are established, allowing for the derivation of dynamic properties over time for each acceleration file. Fig. 3 (a) illustrates the time series of frequency, while Fig. 3 (b) depicts the modal shapes, both pertaining to the base identification of a generic bridge. The significant daily variations in the frequency time series are evident. Hence, it is imperative to mitigate the influence of independent variables such as temperature, humidity, and ambient pressure from the time series data. Fig. 3 (c) demonstrates the removal of environmental effects and outlines the characteristics of the resulting residuals. In the scenario of ideal normalization, the residuals during the training period should primarily comprise normally distributed errors, originating from constraints in identifying the healthy database, alongside marginal EOC effects. The detection of damage is examined through the utilization of control charts, as illustrated in Fig. 3 (d). These charts provide a statistical measure over time, capturing deviations in the distribution of residuals caused by disturbances. By establishing a designated in-control zone, any deviation from this zone, indicated by data points outside of it, signifies potential out-of-control processes, potentially indicative of damage. Thresholds set on the control chart enable the definition of alarms, which bridge supervisors subsequently analyse to assess the extent of structural damage and degradation level used in the traffic network optimisation.

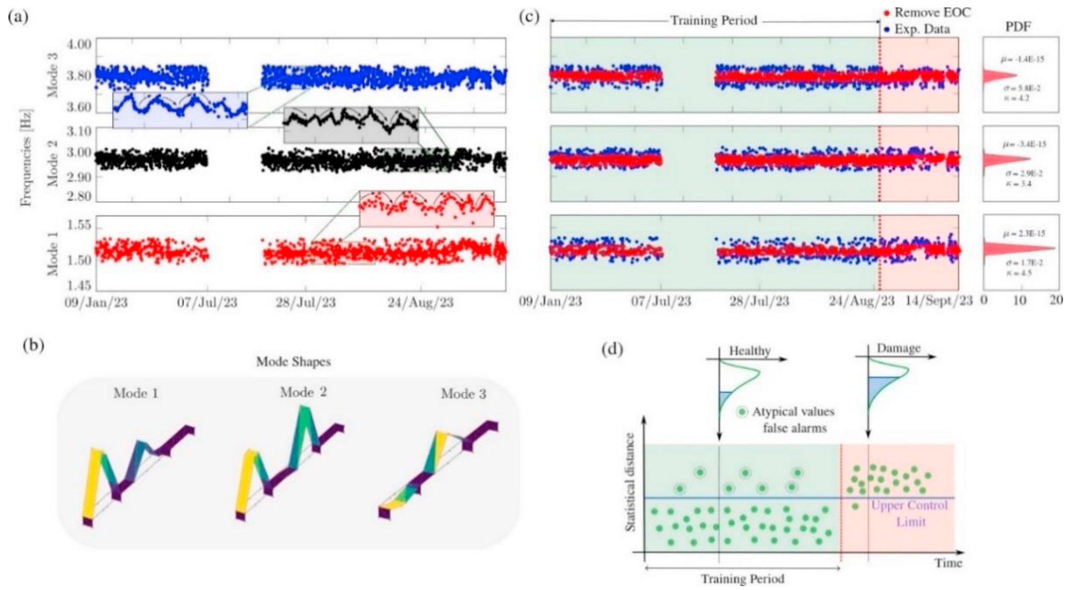

Fig. 3. Tracking the resonant frequencies of a standard bridge from June 9th to September 14th, 2023 (a), along with their respective mode shapes (b). Reduction of EOC in the time series of the first three resonant frequencies of a standard bridge, and the analysis of probability distribution functions (PDFs) for the resulting residuals (c). Control Chart analysis for a continuous SHM system (d).

5.2 Optimisation results

According to the results of the OMA, the degradation costs are set in the optimisation model. A comparison between the different scenarios, listed in Section 4, is performed. The variations of the objective function terms under different scenarios with respect to the nominal condition (scenario 0) are indicated in Table 2. It is worth nothing that a reduction of the degradation cost, due to a lane or complete link closure, corresponds to an increase of transport cost and congestion cost for the users.

In Scenario 3, local roads are assumed unavailable for heavy vehicles. Thus, heavy vehicles are rerouted along highway alternative paths, whose links present a certain level of degradation (indicated by the yellow and orange stars in Fig.2). Therefore, the reduction of degradation cost is lower in this scenario. Scenario 4, avoiding the complete closure of the highest degraded links, presents the lower increase of transport cost and congestion cost with respect to the nominal scenario.

However, finding the best scenario depends on the infrastructure manager's policies and the importance assigned to the different objective function terms in Eq. 1 (weights $\beta_i \quad i = 1 \dots 4$).

Table 2 – Variation of objective function terms under different scenarios with respect to the nominal scenario 0.

Scenario (Sc)	Transport Cost of Highway & Local Roads	Degradation Cost	Congestion Cost
Sc1	+58 %	-41 %	+98 %
Sc2	+23 %	-24 %	+57 %
Sc3	+17 %	-10 %	+86 %
Sc4	+8 %	-22 %	+18 %

6. Conclusion

This paper shows how to integrate decision support functionalities within a digital twin-oriented platform, focusing on the interaction between bridge SHM and traffic management in a highway network. The CEMBOX platform for OMA of bridges is described and an optimisation model is presented to evaluate the best traffic management strategies for the infrastructure manager, considering the impact on the final users. Further developments will consider a sensitivity analysis according to the importance of the objective function terms for the infrastructure manager. In addition, traffic simulation techniques will be applied, and the perceived utility of the final users will be considered in the assignment of the transport demand. Finally, a speed reduction strategy will be considered as an additional mitigation scenario in future works.

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