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ABSTRACT: Transportation infrastructure demands reliable, cost-effective, environmentally friendly, and safe solutions. It is, therefore, crucial to leverage both the knowledge gained from current practices and the potential offered by emerging technologies. This paper uses the scoring system approached in the INFRACOMS project to offer a framework for asset managers and technology providers to identify areas of improvement and make informed decisions regarding selecting and implementing remote condition monitoring solutions. We focus on two technologies for bridges, like bridge weigh-in-motion and digital inspection and centre around four areas: data analysis, visualisation and integration and potential for practical decision-making. Technologies are evaluated based on their intended use, acknowledging that some may have multiple applications due to novel sensor installations or data interpretation/visualisation methods. Consequently, a technology may undergo multiple appraisals within this system. We showcase the benefits of the scoring system, alignment with specific use cases, and potential for broad applicability.

1 INTRODUCTION

The application of consistent, reliable information is a key component of highway asset management. The information and the tools to help interpret and apply data have continuously evolved. However, National Road Authorities (NRAs) are not yet fully exploiting their potential in the highway environment. By bringing these components of sensing and measurement together, NRAs could better understand highway assets and improve reactive and proactive asset management decisions.

This paper describes a scoring system to appraise new technologies mapped for bridges and pavements in the INFRACOMS project (www.infracoms.project.cedr.eu/). INFRACOMS is

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a CEDR Transnational Road Research Programme Call 2021 project (July 2022 – June 2024). It aims to equip NRAs with the capability to leverage the technological evolution in data/ monitoring.

The first action in the project consisted of identifying the information needs, gaps, and priorities of different NRAs in terms of their data collection and monitoring approach and a list of current and emerging measurement technologies. This is reported in Deliverable D1.1 Current Practice, Future Need and Gap Analysis (Arvidsson et al. 2023a).

Commonly used appraisal methodologies that can be used to evaluate the effectiveness, suitability, and potential impact of new technologies for an organisation include Technology Readiness Levels (TRLs), Cost Benefit Analysis (CBA), Life Cycle Cost Analysis (LCCA), Risk Assessment, and Multi-Criteria Decision Analysis (MCDA). Elements of these commonly used methodologies are included in the INFRACOMS Appraisal Methodology.

The INFRACOMS Appraisal Methodology is designed around technology use cases, that is, a particular application of a technology by an NRA. Some technologies may have more than one technology use case within an NRA. In general, each technology use case should be subject to a separate appraisal, as their costs and benefits, risks and limitations will be different. The appraisal methodology was designed and fine-tuned by applying it to several examples of emerging technologies. INFRACOMS will ultimately deliver a Technology Database and a Technology Appraisal Toolkit to CEDR. The database will comprise appraisals and will be the subject of a future publication.

In this paper, a sequence of appraisal methodology developed within the INFRACOMS project is presented and applied to two different technologies. They were mapped as promotional case studies. First, Section 2 presents a concept of the appraisal methodology, following its technical scoring system in Section 3. Section 4 is intended to apply the scoring system for two technologies: Bridge Weigh-In-Motion (BWIM) and COWI Digital inspection platform (CVI). For each technology, a brief description is given, followed by comments on the scoring results and emphasis on future areas of improvement. In the last chapter, the main conclusions from the paper are drawn.

2 APPROACH OF THE INFRACOMS PROJECT

The proposed INFRACOMS Appraisal Methodology is presented in Figure 1. The processes shown in orange boxes represent the core components of an INFRACOMS appraisal. The blue boxes are filtering and prioritisation processes, representing the ways in which the methodology can be tailored to individual NRAs.

An INFRACOMS appraisal has three (3) core processes with increasing levels of detail and complexity: a Pre-Evaluation, an Evaluation, and a Case Study. These core processes apply at the level of the technology use case. Although the appraisal focuses on a specific technology use case, the Pre-Evaluation and Evaluation stages are still considered generic and useful to any NRA considering applying that technology in a similar use case. Case Studies are normally conducted with an individual NRA and are more focused.

The pre-evaluation process is a high-level analysis of the anticipated benefits, limitations and costs and an assessment of the readiness level of the technology for a particular use case from the supplier's perspective. It also scores the technology for the particular use case against the key imperatives of the NRA. Pre-evaluation should be accomplished quite quickly (in perhaps 2 – 3 hours). It would require general knowledge of technologies and their applications and an understanding of the potential applications of the NRA.

The evaluation process is a more detailed breakdown of the technology's benefits, limitations, and cost factors within the proposed use case, including a more in-depth technical evaluation and an assessment of the steps required to implement it in an NRA. It provides an assessment of the readiness level of the technology from the NRA's perspective. Evaluation would take longer (perhaps 2 – 3 days of inputs). It would require input from a specialist or expert in the field and discussion with the technology supplier to gain a full understanding of the technology and its potential application for an NRA. Detail information on this can be found in Arvidsson et al. (2023b).

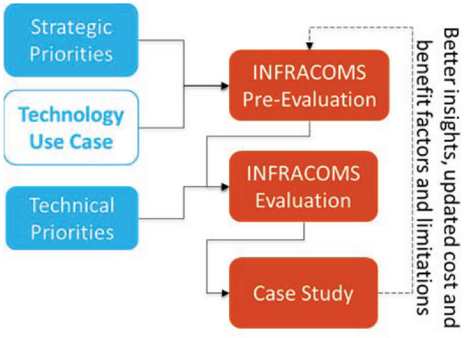

Figure 1. The concept of the INFRACOMS appraisal methodology.

Both the pre-evaluation and evaluation processes also consider the strategic and technical priorities of the NRA. The NRA must establish Strategic Priorities concerning the key imperatives that the NRA wishes to address using emerging technology. Four key imperatives were established in the first action of the project (Arvidsson et al. 2023a): safety, environment, socio-economic, and availability. The NRA must establish Technical Priorities to define its technical priorities concerning the capabilities for using and integrating technology. Four key components that were identified for use in a technical evaluation are (Arvidsson et al. 2023b):

- The need for associated data analysis
- Ease of data visualisation
- Potential for improvement in decision-making
- Ease of data integration.

The ranking between these priorities may differ for different NRAs. A technology may be less relevant for an NRA when it does not address any of the priorities.

3 INFRACOMS SCORING SYSTEM

The current paper focuses only on the technical evaluation of a technology found in the INFRACOMS appraisal methodology. The appraisal components in the technical evaluation include the following items as specified above: The need for associated data analysis, ease of data visualisation, potential for improvement in decision-making, and ease of data integration. Appraisal regarding cost and implementation in an NRA's organisation is for example, not considered in this paper.

The INFRACOMS technical appraisal includes a simple scoring mechanism to allow for the comparison of technologies. The above four components are scored from 1 (lowest) to 5 (highest), indicating the level of technological maturity and potential for improvement. Before scoring, the technology must be described in a specific format to inform the evaluator adequately. An example of the scoring mechanism for the appraisal of data visualisation can be seen below in Figure 2. There are 4 items that should be scored for data visualisation, namely:

- Does the technology come with a visualisation platform?
- Can visualisation data be extracted?
- Current state and prognosis?
- Compliance with client visualisation requirements for decision support?

The concept is that the evaluator will choose a box from each column that they believe best aligns with the current technology from their perspective. The final score is the average of all four items.

A radar diagram where each 'spoke' represents the technical score for a component provides a concise interpretation of the strengths and weaknesses of the technology in each of the technical evaluation areas. Two practical examples of the scoring system are provided in the next chapter.

DATA VISUALIZATION				
DESCRIPTION OF ANALYSIS:				
FINAL SCORING	DOES THE TECHNOLOGY COME WITH A VISUALISATION PLATFORM?	CAN VISUALIZATION DATA BE EXTRACTED?	CURRENT STATE AND PROGNOSIS	COMPLIANCE WITH CLIENT VISUALIZATION REQUIREMENTS FOR DECISION SUPPORT
5 – Visualization provides complete information for decision support / gap closure	Yes, Technology comes with clear and useful visualisation platform. The platform requires some basic training.	Yes, The visualized data can easily be extracted and used for further analysis	The visualization provides information of current state and prognosis can be easily visualised within the platform	The visualization provided gives sufficient and clear information for decision support and open for future developments
4 – Visualization provides complete information for decision support, but some traning are required to interpretate visualization	Yes, Technology comes with clear and useful visualisation platform but the visualization requires detailed technical training to interpret results	Yes, The visualized data can easily be extracted and used for further analysis	The visualization provides information of current state. Prognosis and trends needs to be done manually but this does not require expert staff.	The visualization provided gives sufficient and clear information for decision support
3 –A visualization will provide information for decision support but work is required to develop this	No, But proper visualization/interpretation can be made using simple plotting tools which can generate 2D/3D plots. No specialized staff needs to develop the visualisation platform	Yes, Data can be extracted and used for further analysis but some work are needed to extract the data	The visualization provides information of current state. Prognosis and trends needs to be done manual but this work do not require expert staff.	If the data are visualized it provides sufficient and clear information for decision support
2 – Visualization provides information for decision support, but expert staff are required to interpret visualization	Yes, Technology comes with clear and useful visualisation platform but the visualization requires expert to interpret results	Yes, The visualized data can be extracted and used for further analysis but work from expert staff are needed to extract the data	The visualization provides information of current state. Prognosis and trends needs to be done manual by expert staff.	The visualisation provides information for decision support.
1 – Visualisation only provides partial information for decision support and expert staff are needed to interpret	No,In order to make proper visualisation complex programming are required (e.g. 3D-'as-is'-model based on photogrammetry, possibly paired with AI for automated identification of defects). Expert staff needs to develop the visualisation platform	Yes, The visualized data can be extracted and used for further analysis but work from expert staff are needed to extract the data	The visualization provides information of current state. Prognosis and trends needs to be done manual by expert staff.	The visualisation only provides partial information for decision support; there is a need for additional information

Figure 2. Scoring sheet for data visualisation.

4 APPLICATION OF SCORING SYSTEM

4.1 *Bridge Weigh-in-Motion system*

Bridge Weigh-In-Motion (BWIM) enables measuring the axle and gross weights of vehicles passing over a bridge in the free flow traffic (Moses, 1979, Žnidarič et al. 2017). This technology is based on the dynamic response of the bridge due to moving vehicles in terms of strains, measured with different sensors strategically placed under the bridge. The acquired data is then processed using specialised algorithms to estimate the vehicle data, i.e. gross vehicle weights, axle weight, axle spacing, velocity, etc. Data and information obtained by the BWIM system can be used for two different areas:

- Heavy traffic management.
- Bridge safety assessment.

One significant application of BWIM systems lies in managing heavy traffic. These systems identify overweight vehicles, ensuring the protection of road infrastructure. Moreover, by eliminating the need for vehicles to stop at weigh stations, BWIM facilitates smoother traffic flow. Additionally, it contributes valuable statistical data for traffic policymaking (Figure 3, left).

BWIM systems are also crucial for bridge assessment services, particularly in performing Soft Load Testing (SLT). SLT offers a cost-effective and efficient alternative to traditional load tests by utilising free-flowing traffic data without road closures. This method provides essential parameters for bridge assessment, including strains, influence lines (Figure 3, right), load distribution factors, and dynamic amplification factors.

The effectiveness of BWIM in both heavy traffic management and bridge safety assessment was evaluated using the INFRACOMS scoring system, providing insights into its efficiency and practicality in real-world applications.

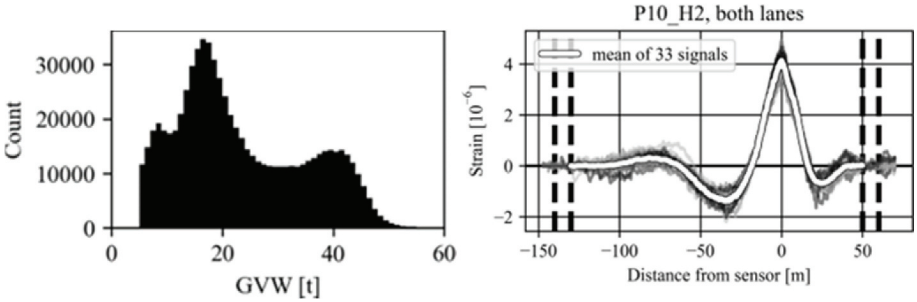

Figure 3. Gross vehicle weight (GVW) and strain data obtained by BWIM for Heavy traffic management (left) and for Bridge Safety assessment (right) (Hekič et al., 2022).

4.1.1 *Scoring results*

As mentioned, BWIM technology offers several layers of data and can be used for both pavements and bridges. The technology scoring was performed similarly, addressing pavement management and bridge management issues. Our findings show that BWIM scores, if we evaluate average ranking values of 2.5 for bridge safety assessment and 4.2 for heavy traffic management (Figure 4). Remember that a score of 5 is reserved for technologies that have achieved full development with little to no room for further advancement.

Although modest, the average score of 2.5 assigned to BWIM in bridge safety assessment has much potential to increase its score. The data for heavy traffic management scores particularly high in Data Visualization and Data Integration, indicating that it is well-suited for comprehensive analysis and seamless synthesis with other data sets. Conversely, the bridge safety assessment data shows lower performance, especially in Data Analysis and Data Integration, suggesting that while it is sufficient for practical decision-making, there is substantial room for improvement in its analytical and integrative capabilities. This suggests that while BWIM has significant capabilities, it demands additional involvement and advanced expertise from bridge engineers to enhance its relevance and improve its standing on the scoring scale.

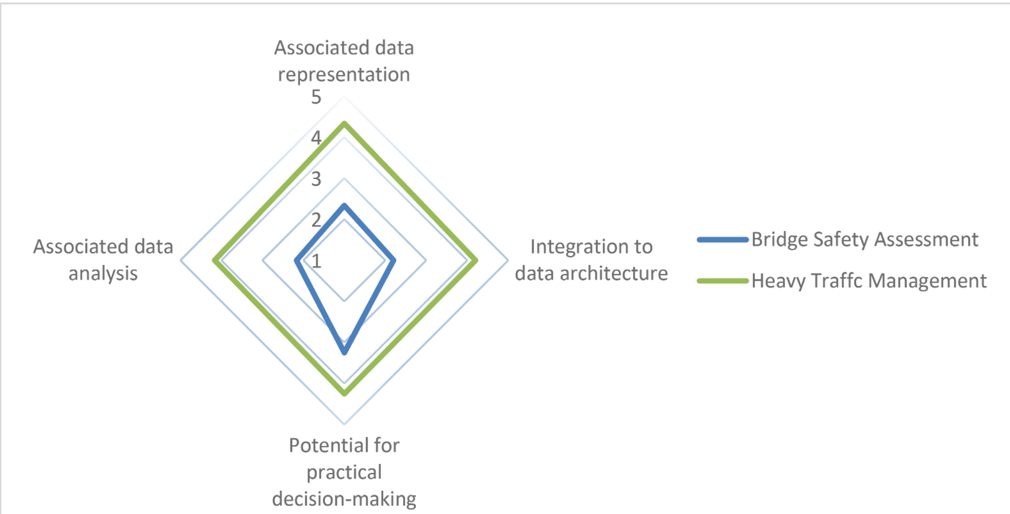

Figure 4. Scoring results for the B-WIM technology are shown on a radar diagram for two different applications.

4.1.2 *Future potential*

The future of BWIM technology is at a promising juncture, with vast potential for enhancing the operational efficiency of road networks. It is an indispensable tool in dual areas, such as Heavy traffic management and Bridge safety assessment. As described in Section 4.1.2, the B-WIM technology already automates key technical aspects like data analysis, visualisation, integration, and practical decision-making. However, for bridge safety assessment services, a gap remains in achieving the desired level of automation for its full practical deployment.

Looking ahead, the modular architecture of the BWIM system harbours the capacity for substantial upgrades, potentially transforming it into a comprehensive Structural Health Monitoring (SHM) system. Its ability to connect a diverse array of sensors and draw a direct correlation between vehicle impact and the consequent structural response — deformations, accelerations, or displacements — sets it apart from other SHM systems. Integrating bridge assessment expertise can unleash the full spectrum of BWIM capabilities, making it an even more powerful instrument in the infrastructure monitoring and maintenance domain. The future enhancements are not just incremental but could mark a paradigm shift in how bridge health is monitored, with BWIM technology offering this advanced step.

4.2 *Digital inspection platform*

The lifetime of structures such as bridges depends on how good we are at maintaining them. If we can postpone decommissioning, we can save massive amounts of time and natural as well as financial resources. An important step in extending the lifetime of structures is to perform reliable and accurate inspections. Traditional inspections are challenged by traffic restrictions, high initial costs (rope access, platform, lift, etc.), subjectivity, and consistency in documentation and working conditions. Establishing a Reality Capture Model or Virtual Twin is important in optimising inspections and moving towards a digital transition within bridge asset management. The model is created from photogrammetrically processed images efficiently collected using camera-mounted unmanned aerial vehicles (UAV).

Within the INFRACOMS project, a case study of digital inspection was taken into account, where COWI's Virtual Inspection platform (CVI) was used. It uses of UAV and artificial intelligence to create a given structure's virtual twin and detect deterioration. The data reveals the structural condition, enabling you to plan for and handle issues while they are still minor and easy as well as inexpensive to correct. By gathering all data in one platform, you can access the full overview from any location and perform your virtual inspections from the office.

First, drones capture high-quality images of the entire structure's surface, which are used to create a photorealistic 3D model. Using a combination of normal colour photography and thermographic images enables you to see "hidden" defects not always visible to the naked eye,

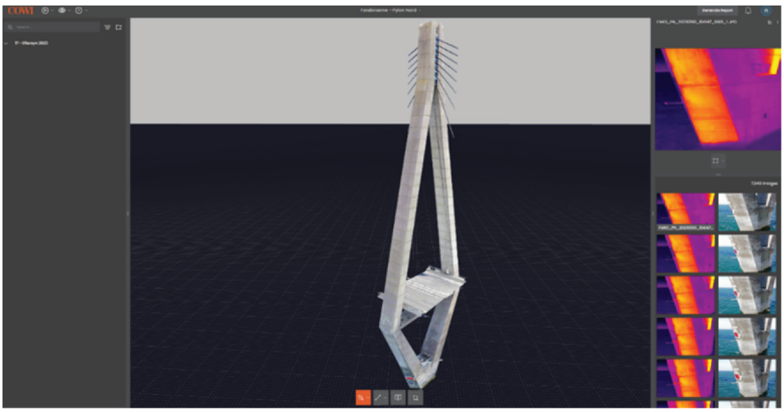

Figure 5. The COWI Virtual Inspection platform illustrates the bridge pylon, where a thermographic camera is used to detect hidden defects.

like delaminated concrete or water seepage. Next, the data is processed, and artificial intelligence is used to detect the defects. Bridge inspection experts then qualify the defects that require repair or further follow-up. All information is gathered in a web-based platform, where data can be shared or revisited at any time.

Inspections using drones on large bridges can significantly reduce the need for lifts, boats, climbing, and rappelling equipment and thereby optimising the inspection process both in terms of safety cost and reliability

Drones with thermography camera provide greater possibility to collect data from the entire structure than hammer tapping, which often only collect data from selected random samples (Figure 5). Direct coupling between photos and geographical position facilitates tracking the development of defects at later stages. Unlike in traditional surveys, where defects are often grouped and only one or few typical pictures are taken for each group, in the COWI Virtual Inspection Platform, pictures are taken for every individual defect.

4.2.1 *Scoring results*

The CVI platform is scored using the INFRACOMS scoring system in the Figure 6. The INFRACOMS scoring is done on a case where the CVI platform was used on a large bridge in Europe.

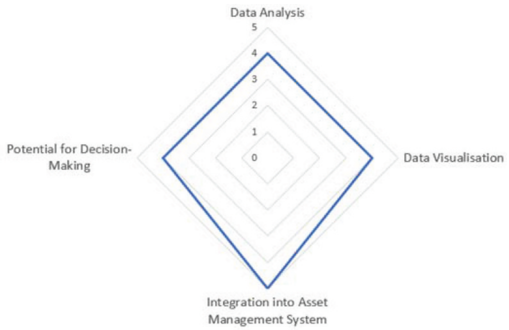

Figure 6. Scoring results for the COWI virtual inspection platform on a radar diagram.

Data visualisations - A 3D Reality Capture Model is created automatically by CVI containing annotated defects and it also includes all RGB – and thermal images. By clicking on any part of the generated 3D model, the 30 best images for the selected spot are shown in a picture panel. In addition, a conventional PDF report is generated in CVI. The report includes a written summary and an auto-generated description of findings based on annotations with additional photos of the defects

Data analysis - Crack detection is performed automatically using a well-trained AI algorithm. An expert, however needs to review and confirm be identified cracks.

Integration into asset management system - In the current case, the data from CVI was not integrated into an existing asset management system. All collected data, including analysis results and expert assessments, where centralised in a web-based platform, facilitating seamless collaboration and data sharing among stakeholders

Potential for decision making - Structural experts need to evaluate the severity and repair urgency of detected defects, enabling informed prioritisation for efficient maintenance planning to ensure that repairs are made at the optimal point in time. Future RCM models can be compared to previous models to identify new defects and defect development to ensure that repairs are made at the optimal point in time. The CVI will improve the quality assurance (QA) process since you have a complete view of the structure and not only pictures taken at locations which are selected by the engineer who is performing the inspection.

4.2.2 *Future potential*

Trials are currently being conducted using smartphones to broaden the use of CVI to smaller structures. While smartphone cameras possess adequate resolution, challenges persist in achieving a finely detailed resolution crucial for precise positioning. This high level of detail is essential for generating a functional 3D model while merging the captured images.

5 CONCLUSIONS

This paper has presented a scoring system for the technical evaluation of technologies which can be used in remote bridge monitoring applications. This scoring system is part of the technology appraisal concept developed within the framework of the INFRACOMS project. It focuses on four key areas: data analysis, data visualisation, decision-making potential, and data integration. These criteria are crucial for assessing the viability and effectiveness of technologies. Two technologies were mapped as appropriate for showcasing the scoring system, i.e. bridge weigh-in-motion systems and digital inspection platforms.

Our findings reveal that each technology has distinct strengths and limitations, as evidenced by the case studies. For instance, bridge weigh-in-motion systems demonstrate high utility in heavy traffic data management but indicate a need for improvement in bridge safety assessment applications since, at this point, it requires the full engagement of the bridge safety assessment experts. This understanding is critical for bridge owners and asset managers to make informed decisions that align with their strategic and technical priorities. Digital Inspection Platform already provides benefits for the landscape bridges at this stage. On the other hand, to scale its application for the whole bridge stock, there should be development in the area of smartphone usage and simplification with respect to the importance of the structure in the whole transport network.

Looking ahead, this scoring system lays the groundwork for more advanced studies and the integration of emerging technologies in the field of bridge or asset management. It holds the potential to guide future research, fostering innovations that further enhance the efficiency, safety, and sustainability of infrastructure management.

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