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INFRACOMS

Innovative and Future-proof Road Asset Condition Monitoring Systems

Report on state-of-the-art data assessment and visualisation methods

Deliverable D3.1

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Innovative & Future-proof Road Asset Condition Monitoring Systems

Report D3.1

Report on state-of-the-art data assessment and visualisation methods

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Executive Summary

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, NRAs are not yet fully exploiting their potential. By bringing these components of sensing and measurement together, NRAs could better understand highway assets and improve both reactive and proactive asset management decisions.

INFRACOMS is a CEDR Transnational Road Research Programme Call 2022 project (July 2022 – June 2024). It aims to equip NRAs with the capability better to leverage the technological evolution in data/monitoring. By investigating the technologies that are becoming available to understand the performance of highway assets, their current and future capabilities and the benefits they bring, INFRACOMS will establish the potential that could be achieved through these technologies. INFRACOMS will develop a database of technologies and provide a structured method to evaluate technologies. It will provide the tools to help NRAs keep the database up to date in future and a roadmap and a maturity assessment tool to help NRAs implement changes.

Effective analysis and visualisation of data is critical for the efficient application of the data provided by carriageway and bridge condition monitoring technologies. It supports better decisions in relation to asset reliability, availability, safety, economy and environment. This report discusses the link between the data provided by monitoring technologies on the properties of assets and how the collected data can be analysed and visualised to provide value in decision support. The next step in the report is to use this understanding to develop an appraisal system which could enable technologies in the INFRACOMS technology database to be appraised (scored) in relation to their abilities for data analysis, visualisation, integration and use in decision support. The presented system is referred to as the D3.1 scoring system. It consists of four components covering data visualisation, data analysis, integration within current data architectures and potential for practical decision-making. The present D3.1 report *primarily* examines the components pertaining to data visualisation and data analysis, while the exploration of the other two components, data architecture and decision support, will be carried out in the D3.2 report.

It is proposed that the D3.1 scoring system could be used to appraise the capability of monitoring technologies to support asset management decisions, and would become an integral component of the INFRACOMS Appraisal Toolkit. It will also be used to further filter the current INFRACOMS Technology Database 2.0 technologies as part of the Appraisal Toolkit as INFRACOMS completes the development of the toolkit/database within WP2.

Glossary

Table 1 summarises the terminology used throughout this document, and the INFRACOMS project.

Table 1. List of terms and meanings.

Term	Meaning
Availability (Carriageways)	The ability of an item to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided (1. This ability depends on the combined aspects of reliability, maintainability and maintenance supportability. 2. Required external resources, other than maintenance resources, do not affect the availability of the item) [EN 13306, PIARC, 2022)
Availability (Bridges)	The proportion of time a bridge is open for service. It does not include failure-related service outages but the ones due to planned maintenance interventions. Alternatively, availability can be measured as the additional travel time required due to an imposed traffic regime on the bridge.
Bridge	A civil engineering structure that affords a passage to pedestrians, animals, vehicles, waterways and services above obstacles or between two points at a height above the ground [COST 323]
BIM / Building Information Modelling	A process supported by various tools and technologies for creating and managing information on a construction project across the project lifecycle.
Carriageway	Part of the road or highway constructed for vehicular use (1. Reserved lanes, lay-bys and passing places are included. 2. The carriageway may include traffic lanes and the shoulder) (PIARC Road Dictionary, PIARC, 2022)
Economy	The financial management of an asset, particularly considering the focussed long-term costs of maintenance activities over the asset's service life.
Environment	The environmental impacts of an asset (bridge or carriageway), in particular in relation to minimizing any adverse influence that the asset has on the environment during the service life of a bridge or carriageway.
Key Condition Data	Data which is of key importance to understanding the condition of an asset and hence its likely availability, reliability etc.
Key Performance Indicator	A term that describes and/or measures the fitness for purpose of the physical asset.
Performance Indicator	A term describing a particular technical characteristic of the condition of an asset.
Reliability (Bridge)	The probability that a bridge will be fit for purpose during its service life. It complements the probability of structural failure (safety), operational failure (serviceability) or any other failure mode. [COST TU 1406 WG3 report, 2018]

Term	Meaning
Remote sensing/ monitoring	The practice of using sensors and software to monitor the condition, performance and behaviour of an asset, remotely rather than directly inspecting or observing the asset in person. Sensors may be attached to or embedded in the asset, but also included other sources such as satellites, aircraft, drones and other mobile sources (e.g. mobile devices, sensors built into vehicles). Remote Sensing/Monitoring can be defined as ”any surveying method which does not require physical contact with the road surface or subsurface” (Schnebele et al, 2015)
Safety	The impacts of an asset (bridge or carriageway) on the health and safety of stakeholders/users. Structural failure is not included by this definition as it is contained within Reliability.
Technical Parameter	A parameter that describes a particular physical value/characteristic of an asset. This may be derived from various measurements, or collected by other forms of investigation
Technology Readiness Level	A method for estimating the maturity of technologies during the acquisition phase of a program. Originally developed by NASA in the 1970s for space exploration technologies.

Abbreviations

Table 2. List of abbreviations.

Abbreviation	Definition
AE	Acoustic Emission
AI	Artificial intelligence
AR	Augmented Reality
CEDR	Conference of European Directors of Roads
CO_2	Carbon dioxide
DT	Digital Twin
IE	Impact echo
INFRACOMS	Innovative & Future-proof Road Asset Condition Monitoring Systems
LiDAR	Light Distance and Ranging
NRA	National Road Authority
PIARC	World Road Association (Permanent International Association of Road Congresses)
TRL	Technology Readiness Level
VR	Virtual Reality
WP	Work Package

1. Introduction

1.1 The INFRACOMS project

The application of consistent, reliable information has been a key component of highway asset management for over 40 years. The information and the tools to help collect, interpret and apply data have continuously evolved during that time. Technologies with the potential to support asset management include remote sensing, intelligent infrastructure monitoring, crowdsourcing, data analytics and visualisation. In this report they are collectively referred to as 'Remote Monitoring Technologies', which is defined in the Glossary. However, National Road Authorities (NRAs) in Europe are not yet fully exploiting their potential in the highway environment to better understand highway assets and to improve both reactive and proactive asset management decisions.

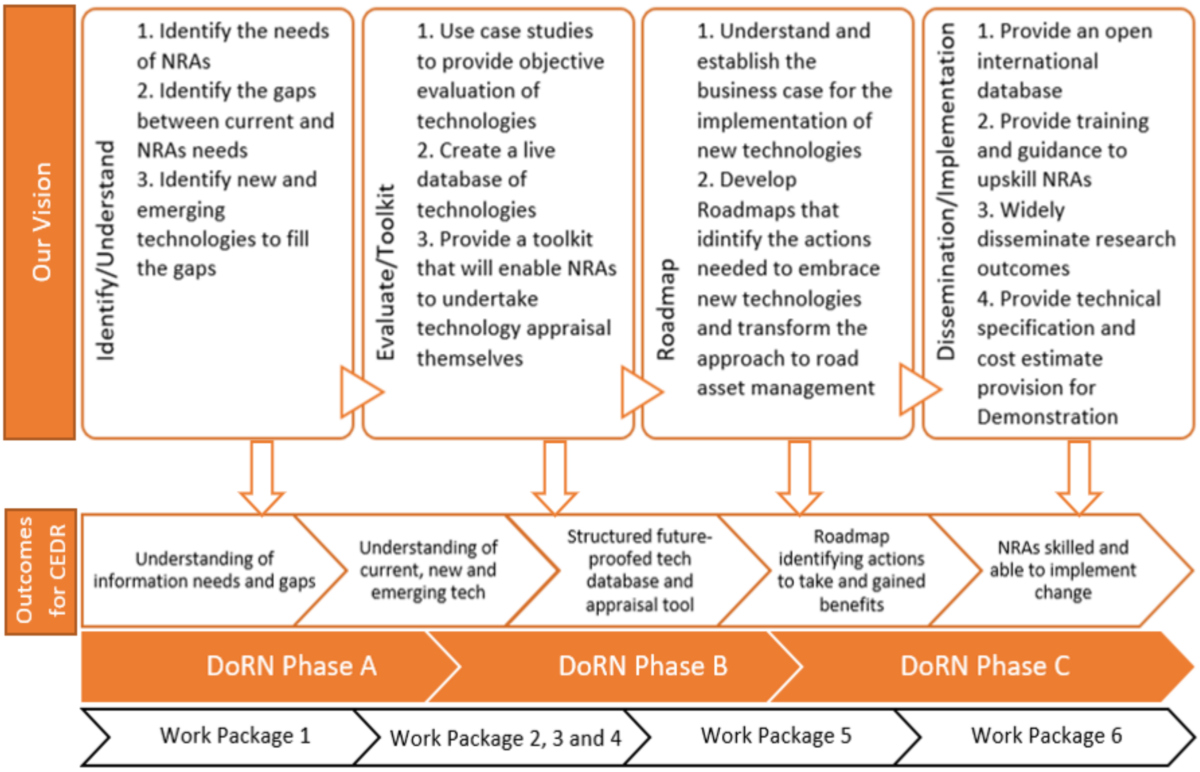

Figure 1. Vision and outcomes of INFRACOMS.

INFRACOMS aims to equip NRAs with the ability to better leverage the technological evolution in data and monitoring. Figure 1 summarises the approach being taken in this project. INFRACOMS is investigating the capabilities and benefits of new technologies for understanding the performance of highway assets. INFRACOMS is establishing a database of these technologies and an Appraisal toolkit to appraise them, to help NRAs assess the costs, benefits and limitations of applying the technologies in their own environments. INFRACOMS will also provide a roadmap to provide strategy and guidance for NRAs to improve their business processes for more effective assessment and implementation of new technologies.

1.2 Overview of INFRACOMS Work Packages

This report (D3.1 - State-of-the-art data assessment and visualisation methods) has been prepared under Work Package 3 of the INFRACOMS project. Figure 2 shows the relationship of the INFRACOMS work packages, tasks and deliverables with respect to WP3.

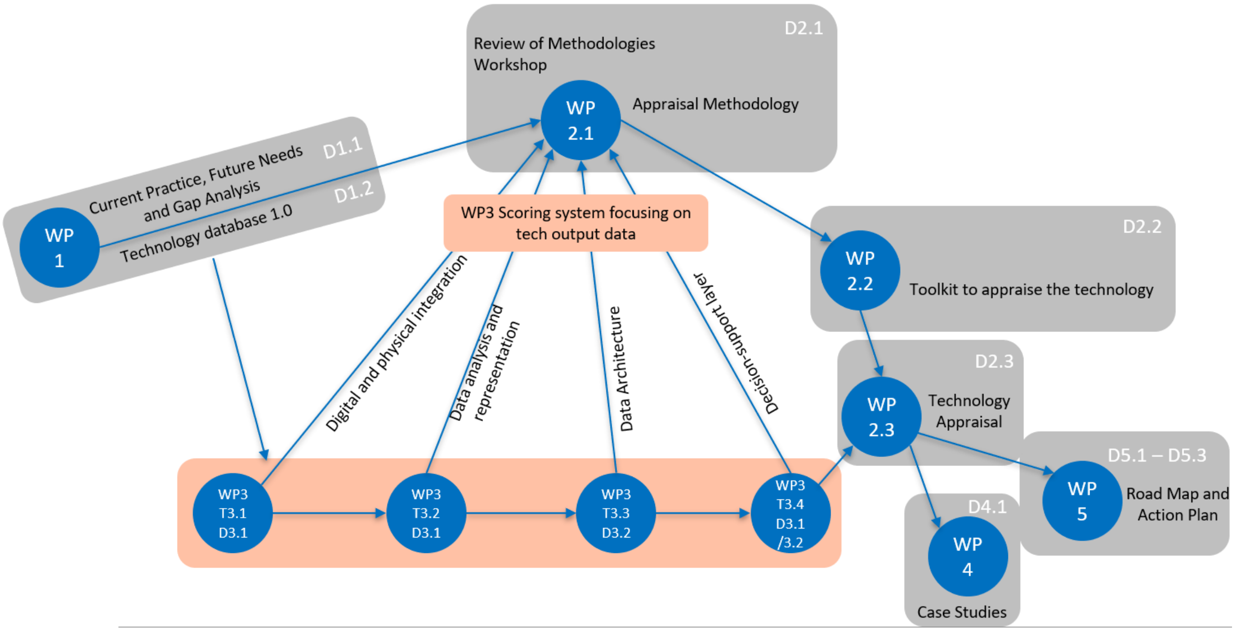

Figure 2. Relationship of WP3 to other Work Packages, Tasks and Deliverables

WP1 report D1.1 on Current Practice, Future Needs and Gap Analysis identified the current priorities and needs of NRAs for the management of carriageway and bridge assets in terms of their approach to data collection and monitoring. It identified gaps in data, challenges in collecting data, and challenges in application of data that is already collected. It also identified technologies that can address those gaps and challenges. WP1 also produced D1.2 - Technology Database. This contained a list of remote condition monitoring technologies and mapped them against the current and future asset management needs / use cases identified in the consultation carried out in WP1.

The INFRACOMS approach is to consider/appraise the capabilities of potential technologies within the context of specific use cases for those technologies. Therefore, WP2 combined the outputs from WP1 with the outcomes of a review of appraisal methodologies and a workshop with NRAs to devise an overall methodology for appraising the technology in the context of use cases. The outcomes of this work are presented in INFRACOMS deliverable D2.1.

This report, D3.1, which is the first deliverable from WP3, considers the data that may be provided by the technologies contained within the Technology Database. It discusses the types of data that may be provided by that technology to describe the physical characteristics of the asset being measured, how that data may be analysed and represented, how easy it would be to integrate that data into asset management systems, and how that data could contribute to a NRA's decision-making processes. The second deliverable from WP3, D3.2, will describe the data architecture considerations with regards to incorporating such data into asset management systems. The D3.2 report will also consider the potential for practical decision support.

INFRACOMS WP2, carried out in parallel with WP3, will develop a toolkit to implement the appraisal methodology as part of W2.2. WP2.3 will apply the toolkit to appraise technologies identified in the (WP1) technology database. WP2 Deliverable D2.2 will describe the appraisal toolkit and user manual.

WP4 will develop real-world case studies for the most promising technologies identified using the methodology.

WP5 will develop a roadmap for the implementation of new technologies for NRAs, and a method for NRAs to assess their maturity in being able to adopt new technologies.

1.3 Scope of this report (INFRACOMS Deliverable D3.1)

The work described in this report was carried out under WP3. WP3 supports the "Evaluate/Toolkit" step of INRACOMS, by considering the "end-to-end" requirements of the technologies that will be appraised via the INFRACOMS toolkit. This includes the interpretation of the data provided by that technology (to support NRA decisions), and the implications for the management and visualisation of that data. This report is structured as follows:

- Section 1 is this introduction
- Section 2 summarises the work package objectives and approach
- Section 3 discusses the challenges and practice associated with the assessment (data interpretation/analysis) and visualisation of data provided by technologies.
- Section 4 proposes a scoring system to appraise the challenges and capacities of technologies in the areas of:
    - Data visualisation
    - Data analysis
    - Data integration (main focus is however in D3.2)
    - Potential for practical decision-making (main focus is however in D3.2)

  It is proposed that this scoring system could be integrated inti the INFRACOMS technology Appraisal Toolkit (see Figure 3). Note : the scoring system in section 4 focusses on data analysis and visualisation. Data architecture and decision support will be addressed in the INFRACOMS report D3.2.

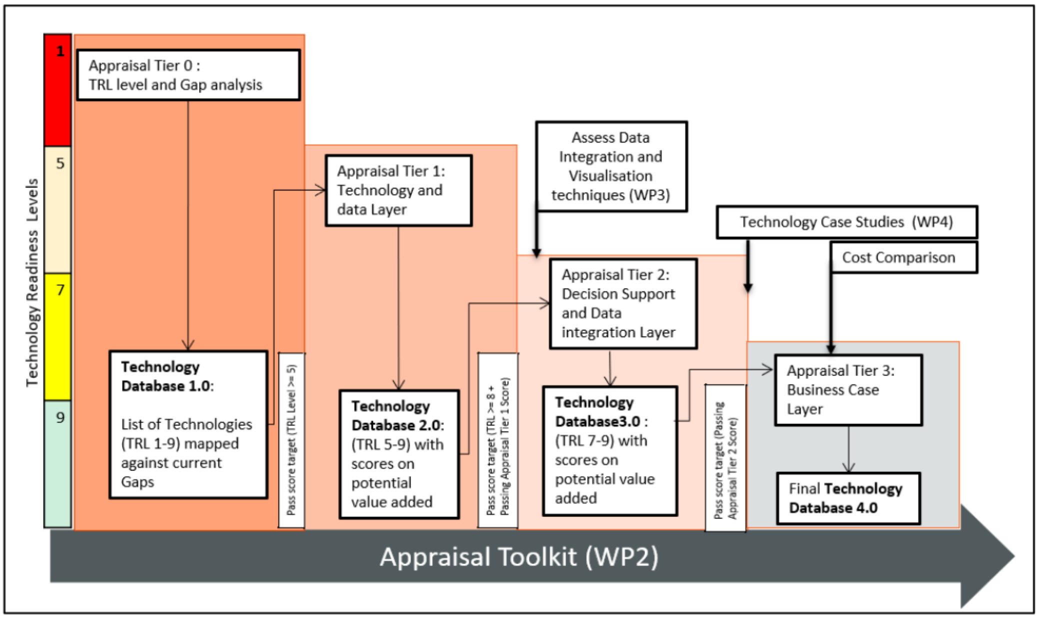

Figure 3. Appraisal toolkit process.

2. Work Package Objectives and Approach

2.1 Objectives

The objectives of WP3 are:

- To asses the processes required for data interpretation and integration (O3.1)
- To identify and assess potential methodologies for data analysis and representation (e.g. AI, BIM, Digital Twin, Virtual and augmented reality) (O3.2)
- To identify and assess data architecture requirements to update asset management systems (O3.3)
- The development of a decision support layer for Tier 3 of the appraisal toolkit (O3.4)

2.2 Approach

Although any assessment of new technology must consider its ability to meet specific technical requirements for (e.g) sensing or measuring asset performance in the light of a required technical need, the successful implementation of that technology in any particular use case will also be influenced by additional factors - including the ability/practicality of implementing/applying the data that the technology provides. WP3 of INFRACOMS focusses on understanding/assessing the ability to integrate data from new technologies (i.e. those being considered by INFRACOMS) into existing asset managements systems, and the data interpretation and visualisation processes required to gain optimal value from the data to support asset management decisions. This report, D3.1, focuses primarily on data interpretation and visualisation, with data integration and decision support considered in greater detail in report D3.2.

The integration and visualisation of asset measurement/condition data can be a complex task. Ideally, it should be possible to condense the data provided by a technology so that it presents the information needed in a manageable way. An effective strategy of data visualisation and integration should allow end users to concentrate efficiently on the relevant content and trends in the data provided. The methodology selected for data visualisation and integration should also be such that it provides a convenient and comprehensible route to integrate the data within asset management systems. This is valid for technologies that allow for discrete (snapshot in time) evaluation and decision-making, as well as continuous systems for real-time or near real-time evaluation and decision-making.

To fulfil the objectives of WP3, we have drawn on the experience of the INFRACOMS consortium members in the design and development of asset management systems and in developing and deploying tailored applications for collecting condition data (eBridge, SSPO, eMost, etc). This has been supplemented with practical knowledge from structural health monitoring projects. This has included drawing on lessons learned from specifying software requirements to visualise, process and interpret the data delivered from more than 1000 real-time data channels by major bridges monitoring technologies, and by developing data interpretation techniques to identify outliers for further investigation. During this process we have considered different asset specific characteristics, both differences between carriageways and bridges, and differences within each asset type - e.g. a few major bridges may need a different setup when compared to thousands of smaller bridges within a NRA portfolio.

A note on "Use Cases". The approach taken by INFRACOMS for the appraisal of technologies is based on "use cases" – i.e. a specific application such as "to provide data on the roughness of the road network to understand user experience”. This ensures that the appraisal is carried out in the context of its intended application. For many technologies that technology will have been developed to support a specific need and may have only one (logical) use case. However, some may have multiple applications, for example where novel installation of sensors or new ways of data interpretation are applied. This approach could therefore allow technologies to be subject to more than one appraisal, and hence more than one appraisal. Note that the selection of the use case is at the option of the NRA, and could be broad if required. Focussing on use cases could appear to add complexity as technologies could appear more than once in the appraisal toolkit. However, it simplifies the individual appraisal process as the person undertaking the appraisal can focus on specific needs. This person is also likely to be associated with the use case and hence have expertise in that area. By focussing on the use case that individual is not required to determine requirements that fall outside their area. However, the toolkit will not prevent the assessor from undertaking a wide ranging appraisal if desired.

3. Data assessment and visualisation requirements

3.1 Introduction

This section considers the data assessment and data visualisation aspects of the application of new technologies that should be taken into account when considering the application of any particular technology for any specific use case. It outlines why such aspects are relevant, the main challenges associated with data assessment and data visualisation and the current trends to successfully overcome them. This is used to establish the foundations for a scoring system that can be applied to assess the data assessment and data visualisation aspects of new technologies – and which is discussed in section 4.

3.2 Link between measured properties and physical asset

Before discussing the relevance of data assessment and data visualisation, it is important to understand the principles of any technology, and how the measured parameters or information link to the response (or performance) of the monitored asset. This basic knowledge is also needed before applying any scoring system to appraise a sensing technology.

The following sub-sections outline relevant characteristics from the monitoring technologies that should be understood prior to proceeding to any appraisal of the ability of that technology to support a particular use case.

3.2.1 Understanding the influence of environmental/operation conditions on measured response/performance

The measurement output from a technology may, in general terms, relate to environmental and/or operational conditions of an asset or to the asset response/performance. Examples of the former include wind or temperature, whereas examples of the latter include strain or displacement. In many cases the required insight is an assessment of the structural performance of an asset. However, to achieve one might need to establish a link between the environmental/operational conditions and the measured responses. For example measuring the displacement of a structure alone in insufficient to infer its (correct) performance. In this case, one needs to establish the link between measured displacements and the conditions (e.g. traffic load, temperature distribution) at the time of the displacement measurement. This can be done by measuring environmental/operational/response data and comparing it with theoretical predictions. In some cases the relationship between measurement output and asset performance can be quite complex, especially if the asset has hidden defects due to a deterioration process that influences the measurement output. In other cases a 1:1 relationship can be established directly.

Hence, for many asset types it is pivotal to have a clear understanding of the parameters being measured by a given technology and how this influences the decision-making process. Moreover, it is important to realize that the data can be erroneous. The error can come from the data analysis algorithms, the sensor installation, or environmental interference etc. An understanding of measurement accuracy is needed to link the measurement to the structural performance.

3.2.2 Spatial coverage

A further key aspect of any sensing technology is to understand its spatial coverage. That is, how representative measurement data /asset response is spatially distributed. This can range from local level (e.g. strains at a weld, identify and measuring the depth of a pothole), to asset level (e.g. mode shapes from a bridge) and finally network level (load distribution captured by Weigh-in-Motion station, traffic flow on network, distribution of rut depths across the network). It is necessary to understand the spatial coverage required to gain insights into an asset's performance – e.g. sometimes this requires that multiple sensors are applied, from the same technology, to provide a picture of the performance of a structure, or that all of lane 1 must be measured to understand the overall need for surface treatments on the network.

3.2.3 Measurement frequency

The measurement frequency associated with a sensing technology influences its suitability for use in a given decision-making process. Higher measurement frequencies can be associated with data storage issues (although these are of decreasing importance given data storage cost reduction), which can be circumvented by saving only relevant post-processed data and storing only a subset of raw data files for data quality traceability. The requirements for sampling frequencies depend on the purpose of the monitoring: long-term deterioration mechanisms (e.g. concrete corrosion or change in roughness of a pavement over time) generally require less frequent data acquisition, whereas data to support operations requires high frequency (e.g. wind data to manage traffic closures on elevated long span bridges, or the development of potholes). Some specific applications (e.g. dynamic characterization of a structure) may require high-frequency measurements, albeit during a short-term duration.

3.2.4 Number of measurement points

Sensing technologies measure at specific points, which may be discrete (e.g. strain gauges, weigh in motion) or not (e.g. pictures to be used within a Digital Image Correlation context). It is therefore relevant to understand this parameter in order to gauge how many sensing instruments are needed in a given application. For instance, if one is tasked to verify the dynamic properties of a structure, several measurement points (accelerometers) will be required (or alternatively if only a limited number of accelerometers are available it will be necessary to move these accelerometers around and keeping a reference one) as a function of which modes are to be assessed. The number of used measurement points shall therefore also be related to the measurement campaign methodology. The number of measurement points is related to the spatial coverage mentioned in section 3.2.2, although they are not identical. In the above example regarding the measurement of dynamic properties, the spatial coverage refers to determining the optimal placement of accelerometers. This placement depends on the desired mode shape of interest. For instance, it would be illogical to position an accelerometer at the midspan of a simply supported bridge if mode 2 is of interest, as the modal deflection at that location would be zero. Another scenario where this distinction arises is in crowd sourcing, where the spatial coverage pertains to the area in which the surveying vehicles operate. On the other hand, the number of measuring points refers to the quantity or density of cars within the measuring fleet.

3.2.5 Additional data

As discussed in section 3.2.1, depending on the purpose of the sensing instrumentation, additional data may be used to contextualize measurements and obtain actionable information. In some cases NRAs already have access to additional data such as temperature records.

It is also relevant to mention that data redundancy is often very important, as access conditions to assets may be difficult and costly, hence the need for redundant instrumentation set-ups to remove uncertainty on the acquired data[1]. This can be achieved by either providing redundancy of the same sensing devices or by considering the deployment of an alternative measurement set-up. To illustrate this, if GPS receivers are deployed to check the long-term stability of a structure, deploying tiltmeters at the locations equipped with GPS will offer redundancy, should GPS-measured displacement be correlated with tilts. Similarly, there may be benefit for carriageway inspections to deploy common sensors across different survey types (e.g. a structural survey device and a surface condition survey device both recording ride quality as part of their sensor suite), so that data can be compared and to assist in the alignment of measurements from different devices.

3.3 Methodologies for data analysis and representation

Data acquisition in an infrastructure management context is motivated by the need for asset managers to allocate limited funds to maintain assets in a safe and fit for purpose condition. The data provided by remote monitoring techniques can reduce the uncertainties associated with the condition and performance of assets. However, to maximize the benefit of remote monitoring, a top-down approach is preferred to specify instrumentation needs. This should start by considering the physical (deterioration) process, or the key performance characteristics, and how acquired data could be used in the assessment and decision-making process. Then, the technologies available should be objectively assessed, and eventually a decision made on the quantity, location and frequency of use of the selected technology.

To illustrate this, if fatigue is a concern in a metallic bridge structure, one should carefully consider the critical details prone to fatigue deterioration before determining the number and location of strain gauges. However, consideration of how the data will be used in the assessment and decision-making process is of equal importance. Building on this example, if fatigue is to be assessed under a S-N approach, it becomes evident that the acquired data will need to be processed by applying a "rainflow" algorithm to calculate stress ranges, which can then be used to estimate fatigue consumptions via a theoretical damage model (the S-N curve in this case). Similarly, the purpose of the instrumentation may also inform how data is to be visualized. In our example, a time-series of the data-driven fatigue consumption plotted together with the traffic load and an extrapolation of future fatigue based on the monitored rates becomes key to understand (and communicate to relevant decision-makers) the conclusions - such as remaining fatigue life and any need for intervention that is identified as a result of the data.

The above considerations highlight the relevance of a top-down approach to remote monitoring, where the purpose of the methodology for assessment informs sensing needs, as well as requirements for data assessment and visualisation/representation. The following sub-sections further elaborate on these two topics.

3.3.1 Data analysis methodologies

Appendix 1 gives an overall presentation of technologies that can be used for visualisation and also to some extent data assessment. Some of these technologies are discussed further in this and the following sections.

As discussed above, data assessment (data processing, interpretation and/or analysis) depends on the purpose of the (remote) instrumentation. Challenges associated with data assessment may arise as a

[1] To elaborate on this, when measurement data reveals unexpected behaviors, it is of paramount importance to have confidence on the data and remove the possibility of polluted readings. An efficient way to achieve this is by having a redundant measurement set-up.

result (e.g.) of collecting large amounts of data, or deploying an instrumentation project without a clear purpose. The first challenge may be addressed by the continuous reduction of costs associated with computer power and data storage, whereas the latter by involving relevant professionals to define the goals, lifecycle, interfaces and limitations of any monitoring initiative before it is implemented.

Different data assessment approaches may be used, depending on the different nature of measurement systems. For instance, in case of direct measurements, i.e. direct measurement of a property in isolation (e.g. temperatures), data assessment may consist of a simple statistical treatment of the data in a predetermined time window (e.g. hourly) to reduce data volumes. Additionally, raw data may be saved periodically (or randomly) to ensure a high-frequency baseline that may be used either for trouble shooting (in case of data quality concerns) or to perform more advanced analysis, should there be a need for this. More advanced analysis may be used with direct measurements. For instance, response data of a structure in terms of accelerations may be processed to estimate natural frequencies via Power Spectral Density (PSD) or Operational Modal Analysis (OMA). Indeed, raw data does not necessarily provide insights. More advanced data processing techniques can equally be used to reduce data, e.g. saving only PSD peaks or identified frequencies and damping ratios via OMA. Examples associated with more complex direct measurements include acoustics monitoring, where different data processing techniques including, for example, times-of-arrival, are needed to identify the origin (e.g. posttensioned steel wire rupture, ongoing corrosion, etc.) of an acoustic signal, or the use of artificial intelligence to detect visual defects or identify assets (signs, lights) in images collected of pavement surfaces or using forward facing imaging systems.

In some instances, different data sources can be fused to extract information. This may be the case for monitoring applications aimed at characterizing the baseline behaviour of an asset. This is useful to ensure the asset performance remains stable over time (i.e. that there is no change attributable to a deterioration process requiring attention) or during extraordinary situations, e.g. existence of construction works adjacent to the instrumented asset. For instance, most cable-supported bridges are equipped with permanent structural monitoring systems. Such systems measure permanently the behaviour of key components. However, it is not reliable to assess in the short-term if e.g. the vertical fluctuations of a bridge deck or the load levels of stay/hangers is as expected, as such responses depend on a variety of conditions, e.g. wind conditions, structural temperatures (average and gradients), traffic conditions, etc. If both the structural response and the environmental/operational conditions that lead to the response are measured, specific data assessment techniques may be deployed to predict the expected response as a function of environmental/operational conditions. This can be used to detect outliers, or long-term trends, that may be useful to trigger additional actions, such as additional assessments, inspections, etc. Multiple linear (Bayesian) regression approaches may be used in this effect, provided a suitable training dataset is available to define the "normal" behaviour or baseline against which outliers will be flagged. More complex approaches (e.g. clustering, neural networks, etc.) may be suitable for specific applications. Approaches that use a machine learning "training-validation-prediction" paradigm rely critically on the available training dataset. In general, sensing schemes (instrumentation) associated with a tangible purpose (e.g. what is the remaining fatigue lifetime of a component, is a component moving as expected, is a cable vibrating below a given threshold, is the roughness of the surface greater than a specific level etc.) provide outcomes that can more readily inform management strategies, in contrast with approaches assessing "changes" or "damage". One of the main reasons of the above is the lack of sensitivity studies to assess the magnitude of changes given typical deterioration levels.

3.3.2 Data visualisation

Data visualisation is important to assist in the interpretation of data provided by measurement instrumentation. For in-depth analyses it it can be used to overcome challenges associated with the large amounts of data that can be acquired with new technologies. It can assist in better understanding of the physical process under consideration, e.g. distribution of wire ruptures in cables from a bridge, distribution of cracks on a concrete structures or across the surface of a pavement. However, it can also be used to simplify the delivery of outputs, conveying clear messages on asset performance to users of the data or managers of the asset.

Different visualisation approaches can be undertaken depending on the spatial coverage of the data, irrespective of whether ad hoc platforms or general solutions[2] are chosen. For instance, data covering a highway network (e.g. pavement roughness) will need an efficient process to support display/navigation of the data across the full network. On the other hand, data associated with a specific asset (e.g. crack distribution on a concrete bridge) may need alternative support such as a geometric representation of the asset, that may be navigated and that contains relevant data such as cracks. Finally, component specific data such as strains of a metallic bridge component, relative movements between a bridge deck and a pier articulated in a bearing, or models of strain in the layers of a pavement, may require simpler visualisation, for example, relying on a combination of time-series and scatter plots. It is relevant to enable the data contextualization when defining visualisation strategies. That is, to be able to visualise the conditions that may explain response data. To illustrate this, traffic loads can be visualized with strain or cable load data, as they are the originating mechanism. The same applies to temperatures and/or ice presence and wind conditions with pavement friction and bridge deck vibrations respectively.

In any case, data visualisation should be linked with the purpose to which the data provided by the the instrumentation is to be applied. Compact visualisations are, by nature, preferable and more informative. Similarly, visualisations shall be efficient so that the operator can make efficient decisions.

Consistent visualisation is also a critical aspect for tracking the condition of an asset or component. Visual supports enabling the representation of (processed) data in time and in space, which can be seen as an instance of the "digital twin" concept, can be very useful not only to document and structure acquired data but also to serve as basis for a consistent data assessment. An example of this can be 3D digital models created with images, for instance taken by autonomous drones, that can be used to navigate a structure at a given point in time. If the same digital inspection is performed in time, i.e. another set of photos are obtained to generate another model instance at a future time, the comparative analysis of images can be used to assess the relative change that may be linked with deterioration, and this can inform asset management strategies. This is equally useful when tracking change in condition on a pavement, where year on-year surveys can be used to track the development of visual deterioration such as surface cracking. In more advanced tools, 3D models can be generated by photogrammetry which can then be analysed by Artificial Intelligence to detect and classify defects such as cracks and their evolution in time.

Other emerging technologies that may facilitate data visualisation are the use of BIM that can be used to create 3D models of road and bridge infrastructure, allowing for detailed analysis and visualisation of asset condition and repair needs. Virtual and augmented reality, which can be used to create

[2] Tools like Tableau or Power BI can be used to create interactive dashboards that allow users to explore asset condition data – they shall be customized .

immersive simulations of roads and bridges, allows engineers and maintenance workers to perform inspections as well as visualise and test repair projects before they are implemented.

Geographic Information Systems (GIS) can be used to analyse and visualize spatial data, for instance to map out the location and condition of infrastructure assets, identify assets or areas in need of repair or maintenance, and track maintenance activities over time.

Different approaches may serve different purposes, ranging from supporting advanced assessments to assisting the navigation of a structure in the field while providing rapid access to historical defects.

4. D3.1 scoring system

4.1 Introduction

Building on the requirements discussed in the previous section, WP3 of INFRACOMS proposes a system (hereafter referred as the "D3.1" scoring system) for the appraisal (scoring) of aspects of technology within the following areas:

1. Data Analysis
2. Data Visualisation
3. Potential for Practical Decision-Making
4. Data Integration into Existing Data Architectures

In this report D3.1 we introduce all of the components of the scoring system. However our main focus in D3.1 is Data Visualisation and Data Analysis. INFRACOMS report D3.2 will provide further detail on Potential for Practical Decision Making and Data Integration into Existing Data Architecture. D3.2 will also present scores for example technologies in the INFRACOMS database.

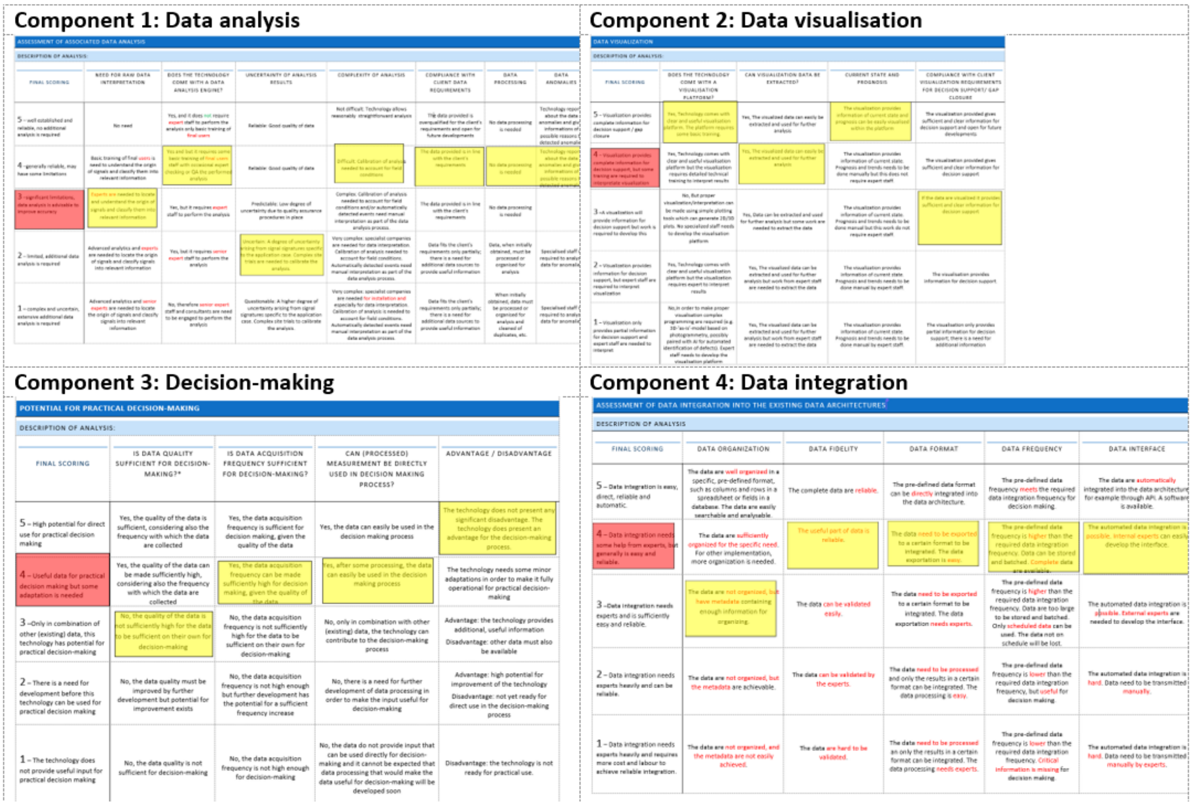

Figure 4. Illustration of the D3.1 scoring system, with final scores indicated (in red) for each of the 4 components, sub scores in yellow. Please refer section4.2-4.4 for details about each scoring component this is only for illustration of how to mark the scoring sheet and illustrate possible spread in each column.

The goal of the scoring system is to provide NRAs with a tool that they can apply to appraise potential monitoring technologies, when considering their application in a specific use case. Figure 4 above shows an example of how the scoring of the four components would look like for a given technology.

It can be seen that the proposed approach is based on the establishment of a set of interim scores for different aspects of each component, drawing on the key needs discussed in the previous section. Hence the scoring system contains several relevant questions that are answered qualitatively by the assessor for each component, ranking in a scale ranging from 1 to 5 (5 being the maximum positive mark). The questions in the four scoring sheets are designed to ensure focus on the relevant subject, and homogeneity in responses (score), given different user backgrounds (see note below).

In a given scoring sheet the different sub scores may be different e.g. in ‘Data visualisation’ a technology might be awarded a score of 5 for "Does the technology come with a visualisation platform" and a score of 1 for "Current state and prognosis" and so forth. The "FINAL SCORING" column (highlighted in red) is a summarization of the individual subscores. Discussions around summarization have suggested options such as taking the arithmetic average of all sub scores, or using the minimum sub score as the final summarization score. It is recommended that the final score is decided via a qualitative assessment / judgement based on what is most important to the NRA undertaking the assessment.

Sections 4.2 to 4.4 below describe the components of the scoring system in detail, whilst section 4.6 shows the application of two of the scoring components to a given technology.

A note on completing the appraisal scoring: It is acknowledged that users of this appraisal tool would not necessarily be domain specialists. However, a certain amount of understanding of the technology under appraisal is required. When developing this appraisal system it was tested by arranging for several people to score the same technologies. It was found that different people scored the same technologies quite differently, even when using the same framework scoring. The main cause of the different scores was, to a large extent, lack of knowledge of the technologies they were trying to score. Therefore, a template was developed which contains questions to facilitate “extraction” of the necessary information for the technology under appraisal. Appendix 2 presents this questionnaire. INFRACOMS recommends that this is used as part of the scoring process. Populating the Appendix 2 questionnaire helps to establish the knowledge required (by the non-expert) to understand the basic aspects of the technology. It is highly recommended that this is completed via discussion/meeting with the technology provider, who can provide a deeper insight, as a simple web search can sometimes be misleading.

4.2 Component 1: Data analysis

The data analysis questions have been developed in the light of the considerations discussed in section 3.3.1. They are listed in Figure 5, along with text guiding the assessor on the approach to scoring for each question. The final scoring is shown on the first column along with a qualitative description of its meaning. The system is designed to provide an overall assessment of a technology from a data analysis perspective. This aggregate scoring enables users to gain a comprehensive understanding of the technology's strengths and weaknesses in analysing (handling and interpreting) data.

At one end of the scale, a final score of 5 signifies that the technology implements "well established and reliable" data analysis, indicating that no further analysis is necessary. This top rating suggests that the technology has demonstrated robust performance, is well understood, and can be trusted to deliver reliable results without the need for additional verification. It represents the gold standard for any technology being assessed. A final score of 1 describes the technology as "complex and uncertain," requiring extensive additional data analysis. This low score indicates a technology that is not well understood, has unreliable results, or is highly complex. In this case, data provided by that technology by require extensive additional analysis to validate its performance and/or interpret its outputs effectively. A further description of the individual columns or subgroups of scoring system from the data analysis perspective can be found below.

Need for raw data interpretation, see Figure 5

> Raw data refers to 'unprocessed, unanalysed and unorganised data that has been collected without any modification or transformation - it is often in its original format as collected by sensors, without any formatting, calculations or summary'. According to the user's requirements, these data may be collected but also needs interpretation in some way. This criterion evaluates the level of proficiency required to understand and translate raw data produced by technology. The spectrum here ranges from a scenario where no interpretation is necessary by the user, to one where interpretation requires the involvement of senior experts (often external consultants or experts) with advanced analytics capabilities to make sense of the data and translate them into meaningful information.

Does the technology come with a data analysis engine?, see Figure 5

> A data analysis engine is used here as a term for tools or software that help to Interpret the data collected and to make or support interpretation od the data. This appraises the ability of the technology in question to provide an inbuilt data analysis (an "analysis engine") and, if so, what is the extent of expertise needed to operate it effectively. The range extends from situations where only basic user training is required to apply this to situations where senior expert staff and outside consultants must be engaged for successful data interpretation and analysis.

Uncertainty of analysis results, see Figure 5

> All measurements have some level of uncertainty, which can be reduced by implementing specific quality assurance procedures, including more or less complex calibration. This element appraises the trustworthiness of data and the degree of certainty that can be associated with the analysis outcomes. At one end of the scale, the technology may provide reliable data of good quality. At the other end, there is a possibility for a considerable degree of uncertainty, for example as a result of the need for complex site trials to calibrate the information (signals/data) provided.

Complexity of analysis, see Figure 5

This scoring factor reflects the complexity of the data analysis, appraising the technology's ability to support interpretation of the data it provides. It ranges from situations where technology allows straightforward analysis to circumstances where specialized companies are necessary for interpretation, and specific calibrations are needed to accommodate changes in field conditions.

Compliance with client data requirements, see Figure 5

Road agencies must make several decisions related to managing their road networks, regardless of being operators or network owners. Data should be collected to support specific needs and decision-making processes. This step appraises the extent to which the data provided by the technology is likely to align with end user (client) needs, i.e. is the data provided actually required/provide value to understanding of assets and can the incoming data help to close the actual gap. At one extreme, the data surpasses the agency' needs and opens doors for future developments and thereby additional value. At the other extreme, the data partially fits the requirements, highlighting the need for additional data sources to garner useful insights.

Data processing, see Figure 5

This component considers the extent of data processing required once the data is acquired. It could range from no need for processing at all, to scenarios where the data, initially obtained, needs to be organized, processed, and cleansed of duplicates or errors before analysis can take place.

Data anomalies, see Figure 5

Next to the data processing score, this factor examines the technology's capability to detect and report data anomalies, along with the need for specialized staff to identify and comprehend these anomalies. On one end of the scale, the technology is capable of autonomously detecting and explaining anomalies. On the other end, specialized staff are needed to analyse and interpret anomalies.

ASSESSMENT OF ASSOCIATED DATA ANALYSIS							
DESCRIPTION OF ANALYSIS:							
FINAL SCORING	NEED FOR RAW DATA INTERPRETATION	DOES THE TECHNOLOGY COME WITH A DATA ANALYSIS ENGINE?	UNCERTAINTY OF ANALYSIS RESULTS	COMPLEXITY OF ANALYSIS	COMPLIANCE WITH CLIENT DATA REQUIREMENTS	DATA PROCESSING	DATA ANOMALIES
5 – well established and reliable, no additional analysis is required	No need	Yes, and it does not require expert staff to perform the analysis only basic training of final users	Reliable: Good quality of data	Not difficult: Technology allows reasonably straightforward analysis	The data provided is overqualified for the client's requirements and open for future developments	No data processing is needed	Technology reports about the data anomalies and gives informations of possible reasons to detected anomalies
4 –generally reliable, may have some limitations	Basic training of final users is need to understand the origin of the incoming data and classify them into relevant information	Yes and but it requires some basic training of final users staff with occasional expert checking or QA the performed analysis	Reliable: Good quality of data	Difficult: Calibration of analysis needed to account for field conditions	The data provided is in line with the client's requirements	No data processing is needed	Technology reports about the data anomalies and gives informations of possible reasons to detected anomalies
3 –significant limitations, data analysis is advisable to improve accuracy	Experts are needed to locate and understand the origin of the incoming data and classify them into relevant information	Yes, but it requires expert staff to perform the analysis	Predictable: Low degree of uncertainty due to quality assurance procedures in place	Complex: Calibration of analysis needed to account for field conditions and/or automatically detected events need manual interpretation as part of the data analysis process.	The data provided is in line with the client's requirements	No data processing is needed	
2 – limited, additional data analysis is required	Advanced analytics and experts are needed to locate the origin of the incoming data and classify the incoming data into relevant information	Yes, but it requires senior expert staff to perform the analysis	Uncertain: A degree of uncertainty arising from signal signatures specific to the application case. Complex site trials are needed to calibrate the analysis.	Very complex: specialist companies are needed for data interpretation. Calibration of analysis needed to account for field conditions. Automatically detected events need manual interpretation as part of the data analysis process.	Data fits the client's requirements only partially; there is a need for additional data sources to provide useful information	Data, when initially obtained, must be processed or organised for analysis	Specialised staff is required to analyse data for anomalies
1 – complex and uncertain, extensive additional data analysis is required	Advanced analytics and senior experts are needed to locate the origin of the incoming data and classify the incoming data into relevant information	No, therefore senior expert staff and consultants are need to be engaged to perform the analysis	Questionable: A higher degree of uncertainty arising from signal signatures specific to the application case. Complex site trials to calibrate the analysis.	Very complex: specialist companies are needed for installation and especially for data interpretation. Calibration of analysis is needed to account for field conditions. Automatically detected events need manual interpretation as part of the data analysis process.	Data fits the client's requirements only partially; there is a need for additional data sources to provide useful information	When initially obtained, data must be processed or organised for analysis and cleaned of duplicates, etc.	Specialised staff is required to analyse data for anomalies

Figure 5. Questions and scoring descriptions for D3.1 scoring component “Assessment of associated data analysis”.

4.3 Component 2: Data visualisation

The data visualisation component questions for scoring have been developed taking into account the considerations discussed in section 3.3.2. They are listed in Figure 6 along with text guiding the scoring for each question. The final scoring is found on the first column along with a qualitative description of its meaning. A further description of the individual columns can be found below.

Does the technology come with a visualisation platform?, see Figure 6 .

A technology that comes with a data visualisation platform may provide a user-friendly interface that simplifies the process of interacting with the technology or the data provided. It eliminates the need for extensive training or specialized technical knowledge, making it accessible to a wider range of users. A visualisation platform that is developed directly for a technology often allows users to quickly grasp the functionality, customize views, and manipulate data without being overwhelmed by complex software or programming requirements. Possible integration of the visualisation platform is treated later.

Due to the above, technologies that come with a visualisation platform are scored relatively high.

Can visualisation data be extracted?, see Figure 6

A visualisation platform may not visualise the collected data in an optimal manner which could be required for the intended use case or for efficient decision-making. Furthermore, if data can be extracted it can be integrated with other data sources, enabling comprehensive analysis and collaboration (perhaps expanding its capability and use cases). By combining data from different measuring technologies, a holistic view can be generated that can enhance understanding and facilitate collaborative decision-making. In this context technologies where data extraction is uncomplicated are scored relatively high.

Current state and prognosis, see Figure 6

Prognosis (prediction of future state) is of importance when making decisions on assets since it provides insights into future performance, and constitutes a basis for special inspections, maintenance requirements, life cycle costs and expected lifespan of assets. This information is used for efficient planning of interventions and allocating resources, ensuring that the assets are properly maintained, repaired, or replaced at the optimal point in time. In this context technologies where both current state and prognosis can be easily visualized is scored highly.

Compliance with client visualisation requirements for decision support, see Figure 6

A clear and intuitive understanding through visualisation can ease decision-support. However, in this context it is important that the visualisation focuses on the part of the data that is of essence to perform a decision on (provide sufficient knowledge on) on the actual gap that is of NRA concern. In addition, it is seen as a benefit if a visualisation platform allows for future developments such as integrating the collected data with other available data to develop a better understanding.

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 6. Questions and scoring descriptions for D3.1 scoring component "Data Visualisation".

4.4 Component 3: Potential for practical decision-making

The questions associated with the potential for practical decision-making scoring are listed in Figure 7, along with text guiding the scoring for each question. The final scoring is found in the first column along with a qualitative description of its meaning. A further description of the individual columns and the development of this scoring sheet will be presented in more detailed in report D3.2

4.5 Component 4: Data integration into existing data architecture

The questions associated with the data integration scoring are listed in Figure 8, along with text guiding the scoring for each question. The final scoring is found in the first column, along with a qualitative description of its meaning. A further description of the individual columns and the development of this scoring sheet will be presented in more detail in report D3.2.

POTENTIAL FOR PRACTICAL DECISION-MAKING

DESCRIPTION OF ANALYSIS:

FINAL SCORING	IS DATA QUALITY SUFFICIENT FOR DECISION-MAKING?*	IS DATA ACQUISITION FREQUENCY SUFFICIENT FOR DECISION-MAKING?	CAN (PROCESSED) MEASUREMENT BE DIRECTLY USED IN DECISION MAKING PROCESS?	ADVANTAGE / DISADVANTAGE
5 – High potential for direct use for practical decision making	Yes, the quality of the data is sufficient, considering also the frequency with which the data are collected	Yes, the data acquisition frequency is sufficient for decision making, given the quality of the data	Yes, the data can easily be used in the decision making process	The technology does not present any significant disadvantage. The technology does present an advantage for the decision-making process.
4 – Useful data for practical decision making but some adaptation is needed	Yes, the quality of the data can be made sufficiently high, considering also the frequency with which the data are collected	Yes, the data acquisition frequency can be made sufficiently high for decision making, given the quality of the data	Yes, after some processing, the data can easily be used in the decision making process	The technology needs some minor adaptations in order to make it fully operational for practical decision-making
3 –Only in combination of other (existing) data, this technology has potential for practical decision-making	No, the quality of the data is not sufficiently high for the data to be sufficient on their own for decision-making	No, the data acquisition frequency is not sufficiently high for the data to be sufficient on their own for decision-making	No, only in combination with other (existing) data, the technology can contribute to the decision-making process	Advantage: the technology provides additional, useful information Disadvantage: other data must also be available
2 – There is a need for development before this technology can be used for practical decision making	No, the data quality must be improved by further development but potential for improvement exists	No, the data acquisition frequency is not high enough but further development has the potential for a sufficient frequency increase	No, there is a need for further development of data processing in order to make the input useful for decision-making	Advantage: high potential for improvement of the technology Disadvantage: not yet ready for direct use in the decision-making process
1 – The technology does not provide useful input for practical decision making	No, the data quality is not sufficient for decision-making	No, the data acquisition frequency is not high enough for decision-making	No, the data do not provide input that can be used directly for decision-making and it cannot be expected that data processing that would make the data useful for decision-making will be developed soon	Disadvantage: the technology is not ready for practical use.

* Supplementary explanation is provided on the last sheet which is related to data architecture

Figure 7. Questions and scoring descriptions for D3.1 scoring component "Potential for practical decision-making".

ASSESSMENT OF DATA INTEGRATION INTO THE EXISTING DATA ARCHITECTURES (INPUT!!!!! WHAT DATA ARCHITECTURE IS USED AS BASIS IROADS OR WALLONIA)

DESCRIPTION OF ANALYSIS

FINAL SCORING	DATA ORGANIZATION	DATA FIDELITY	DATA FORMAT	DATA FREQUENCY	DATA INTERFACE
5 – Data integration is easy, direct, reliable and automatic.	The data are well organized in a specific, pre-defined format, such as columns and rows in a spreadsheet or fields in a database. The data are easily searchable and analysable.	The complete data are reliable.	The pre-defined data format can be directly integrated into the data architecture.	The pre-defined data frequency meets the required data integration frequency for decision making.	The data are automatically integrated into the data architecture, for example through API. A software is available.
4 – Data integration needs some help from experts, but generally is easy and reliable.	The data are sufficiently organized for the specific need. For other implementation, more organization is needed.	The useful part of data is reliable.	The data need to be exported to a certain format to be integrated. The data exportation is easy.	The pre-defined data frequency is higher than the required data integration frequency. Data can be stored and batched. Complete data are available.	The automated data integration is possible. Internal experts can easily develop the interface.
3 –Data integration needs experts and is sufficiently easy and reliable.	The data are not organized, but have metadata containing enough information for organizing.	The data can be validated easily.	The data need to be exported to a certain format to be integrated. The data exportation needs experts.	The pre-defined data frequency is higher than the required data integration frequency. Data are too large to be stored and batched. Only scheduled data can be used. The data not on schedule will be lost.	The automated data integration is possible. External experts are needed to develop the interface.
2 – Data integration needs experts heavily and can be reliable.	The data are not organized, but the metadata are achievable.	The data can be validated by the experts.	The data need to be processed and only the results in a certain format can be integrated. The data processing is easy.	The pre-defined data frequency is lower than the required data integration frequency, but useful for decision making.	The automated data integration is hard. Data need to be transmitted manually.
1 – Data integration needs experts heavily and requires more cost and labour to achieve reliable integration.	The data are not organized, and the metadata are not easily achieved.	The data are hard to be validated.	The data need to be processed an only the results in a certain format can be integrated. The data processing needs experts.	The pre-defined data frequency is lower than the required data integration frequency. Critical information is missing for decision making.	The automated data integration is hard. Data need to be transmitted manually by experts.

Figure 89. Questions and scoring descriptions for D3.1 scoring component "Data integration into existing data architecture".

4.6 Example technology and use case – Acoustic monitoring for post-tensioned steel wire rupture detection of bridge cables

This section illustrates the application of the appraisal process to an example technology and use case - Acoustic monitoring, for post-tensioned steel wire rupture detection of bridge cables. In this report (D3.1) we focus on the Data Analysis (Figure 10) and Data Visualisation (Figure 11) components. The "Data integration into existing data architecture" and "Potential for practical decision-making" components wil be discussed further in D3.2. As discussed above, the appraisal is supported by a technical questionnaire to support understanding of the technology – this is presented in Appendix 3 for this acoustic monitoring example.

With regards to Data Analysis (Figure 10), acoustic monitoring for post-tensioned steel wire ruptures requires highly specialised personnel to i) define the measurement set-up and ii) to define the data triaging required to filter environmental and operational effects from the signals that contain signatures of wire breaks. In many cases, on-site tests consisting of the controlled rupture of some wire breaks are needed to characterize the wire break signature, given the specific environment where the system is installed. Given the limitation of the technology, i.e. it can only detect wire ruptures from its installation (it does not provide an absolute condition of the cable), often the outcome from acoustic monitoring should be complemented with other investigations such as endoscope tests or, if the tendon geometry allows it, magnetic tests to detect cable section losses. This results in the need for specialized companies to perform complex analysis which may need to be supplemented with other investigations. This is reflected in the overall score of "2" for Data Analysis, highlighting that, for this technology and use case, additional data analysis is required (e.g. other type of tests to confirm absolute condition) to support decisions on asset performance. This does not necessarily mean that the technology is not useful in this use case, as it may be very advantageous in some cases where for other types of measurement are impractical. This highlights also that the decision to apply a given technology shall be performed from a top down approach, considering needs that may span beyond the D3.1 appraisal (e.g. cost-benefit considerations, etc.).

Figure 11 summarises the appraisal of data visualisation, which has resulted in a scoring of 3, meaning that visualisation provides information for decision support but work is required to develop this. In effect, the outcome of the data processing may be uncertain, but it can be easily represented in visual reports (either plots or geometrical models) to show the evolution of wire ruptures for the different cables instrumented. This usually requires customization and may be used to inform asset management strategies.

ASSESSMENT OF ASSOCIATED DATA ANALYSIS							
DESCRIPTION OF ANALYSIS:							
FINAL SCORING	NEED FOR RAW DATA INTERPRETATION	DOES THE TECHNOLOGY COME WITH A DATA ANALYSIS ENGINE?	UNCERTAINTY OF ANALYSIS RESULTS	COMPLEXITY OF ANALYSIS	COMPLIANCE WITH CLIENT DATA REQUIREMENTS	DATA PROCESSING	DATA ANOMALIES
5 – well established and reliable, no additional analysis is required	No need	Yes, and it does not require expert staff to perform the analysis only basic training of final users	Reliable: Good quality of data	Not difficult: Technology allows reasonably straightforward analysis	The data provided is overqualified for the client's requirements and open for future developments	No data processing is needed	Technology reports about the data anomalies and gives informations of possible reasons to detected anomalies
4 –generally reliable, may have some limitations	Basic training of final users is need to understand the origin of signals and classify them into relevant information	Yes and but it requires some basic training of final users staff with occasional expert checking or QA the performed analysis	Reliable: Good quality of data	Difficult: Calibration of analysis needed to account for field conditions	The data provided is in line with the client's requirements	No data processing is needed	Technology reports about the data anomalies and gives informations of possible reasons to detected anomalies
3 –significant limitations, data analysis is advisable to improve accuracy	Experts are needed to locate and understand the origin of signals and classify them into relevant information	Yes, but it requires expert staff to perform the analysis	Predictable: Low degree of uncertainty due to quality assurance procedures in place	Complex: Calibration of analysis needed to account for field conditions and/or automatically detected events need manual interpretation as part of the data analysis process.	The data provided is in line with the client's requirements	No data processing is needed	Technology reports about the data anomalies
2 – limited, additional data analysis is required	Advanced analytics and experts are needed to locate the origin of signals and classify signals into relevant information	Yes, but it requires senior expert staff to perform the analysis	Uncertain: A degree of uncertainty arising from signal signatures specific to the application case. Complex site trials are needed to calibrate the analysis.	Very complex: specialist companies are needed for data interpretation. Calibration of analysis needed to account for field conditions. Automatically detected events need manual interpretation as part of the data analysis process.	Data fits the client's requirements only partially; there is a need for additional data sources to provide useful information	Data, when initially obtained, must be processed or organised for analysis	Specialised staff is required to analyse data for anomalies
1 – complex and uncertain, extensive additional data analysis is required	Advanced analytics and senior experts are needed to locate the origin of signals and classify signals into relevant information	No, therefore senior expert staff and consultants are need to be engaged to perform the analysis	Questionable: A higher degree of uncertainty arising from signal signatures specific to the application case. Complex site trials to calibrate the analysis.	Very complex: specialist companies are needed for installation and especially for data interpretation. Calibration of analysis is needed to account for field conditions. Automatically detected events need manual interpretation as part of the data analysis process.	Data fits the client's requirements only partially; there is a need for additional data sources to provide useful information	When initially obtained, data must be processed or organised for analysis and cleaned of duplicates, etc.	Specialised staff is required to analyse data for anomalies

Figure 10. Illustration of scoring results for "Data analysis" D3.1 component applied to acoustic monitoring for wire rupture detection in bridge cables.

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/ GAP CLOSURE
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 11. Illustration of scoring results for "Data visualisation" D3.1 component applied to acoustic monitoring for wire rupture detection in bridge cables.

5. Conclusions

To equip NRAs with the ability to better leverage the technological evolution in data and monitoring, INFRACOMS is establishing a database of technologies and a toolkit to help NRAs appraise them. Any assessment of new technology must consider its ability to meet specific technical requirements. However, the successful implementation of that technology in any particular use case will also be influenced by the ability/practicality of implementing/applying the data that technology provides. The work presented in this report, carried out under WP3 of INFRACOMS, has focussed on understanding/assessing the ability to integrate data from new technologies, in particular the data interpretation and visualisation processes.

Effective analysis and visualisation of data is critical for the efficient application of the data provided by carriageway and bridge condition monitoring technologies. It supports better decisions in relation to reliability, availability, safety, economy and environment. This work has discussed the link between the ability of technologies to measure the physical properties of assets, and the approaches that are/can be provided for data assessment (processing, interpretation and analysis) and visualisation. An appraisal system (referred to as D3.1 scoring) has therefore been developed to assess technologies in this context.

The appraisal system consists of four components that consider Data Visualisation and Data Analysis, Potential for Practical Decision Making and Data Integration into Existing Data Architecture. Before appraising a given technology/use case with this sytem, we have recommended that appraisers complete a questionnaire that will help to establish the technical foundations necessary to appraise that technology - this questionnaire has been provided Appendix 2. In this report D3.1 we have introduced all of the components of the appraisal system and have provided detail on appraisal process for the Data Visualisation and Data Analysis components. INFRACOMS report D3.2 will provide further detail on Potential for Practical Decision Making and Data Integration into Existing Data Architecture.

It is proposed that the D3.1 scoring system could be used to appraise the capability of monitoring technologies to support asset management decisions, and would become an integral component of the INFRACOMS Appraisal Toolkit. It will also be used to further filter the current INFRACOMS Technology Database 2.0 technologies as part of the Appraisal Toolkit as INFRACOMS completes the development of the toolkit/database within WP2.

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Appendix 1 Technologies and visualisation methods

Augmented Reality (AR):
AR can be used to visualise the condition of carriageways and bridges on site or at the office – in the latter case it is similar to VR (see below). It can overlay data collected from various sources onto the physical structures, providing a more immersive and interactive experience for engineers and maintenance workers. AR is primarily used for training purposes at production facilities but has recently (2021-2022) been tested in connection with onsite bridge inspections. The technology needs to mature in order to make it efficient on site during challenging light conditions.

Virtual Reality (VR):
VR can be used to perform immersive inspections and create immersive simulations of carriageways and bridges, allowing engineers and maintenance workers to visualise and test repair projects before they are implemented.

Digital Twins (DT):
Digital twins can be used to create virtual replicas of carriageways and bridge infrastructure, allowing for detailed analysis of asset condition and identification of repair needs.

Building Information Modelling (BIM): BIM can be used to create data-enriched 3D models of carriageway and bridge infrastructure, allowing for detailed analysis (e.g. cost estimates) and visualisation of asset condition and repair needs.

Geographic Information Systems (GIS):
GIS is a tool that allows for the analysis and visualisation of spatial data. In the context of carriageway and bridge maintenance, GIS can be used to map out the location and condition of infrastructure assets, identify areas in need of repair or maintenance, and track maintenance activities over time.

Light Detection and Ranging (LiDAR):
LiDAR technology can be used to create high-resolution 3D models of carriageway and bridge infrastructure, allowing for detailed analysis of the condition of the assets and identification of areas in need of repair.

Artificial Intelligence (AI):
AI models can be used to analyse data collected from various sources, including GIS, LiDAR, and drones. It can identify defects, patterns and trends that can help to predict future inspection and maintenance needs and prioritize repair projects. It is important that the AI models are trained for similar application, subjects like similar image resolution and lighting conditions is important for crack detection on the surface of concrete structures.

Computer Vision:
Computer vision is a subfield of AI, which can be used to analyse images and video of carriageway and bridge infrastructure, enabling automated detection of damage or wear and tear. Examples of software applying computer vision technology include OpenCV and Tensorflow.

Generative Pre-trained Transformers (GPT):
GPT is a subfield of AI and Large Language Models, which can be used for natural language processing (NLP). GPTs include Google Bard by Google, GPT-3/4 by OpenAI and LLaMa by Meta. By the use of neural networks with many parameters, these models can process complex textual information, enabling risk assessments, market forecasts, etc. The combination of NLP and state-of-the-art visualisation methods offers a compelling avenue for the enhancement of asset management. Their

integration signifies a paradigm shift in the asset management industry, leveraging AI to drive informed and timely decisions.

Photogrammetry:
Photogrammetry is used for processing images to create accurate 3D models and orthomosaic maps, which can be used for immersive inspection identifying required on site inspection, maintenance or repair. Using drones for capturing images has the advantage that they can be captured quickly, efficiently and from difficult-to-reach areas, such as the underside of a bridge or the top of a Pylon. This can lead to cost savings, as defects can be identified and addressed before they become an immediate problem, and improved safety for asset users as well as inspection personnel.

Data visualisation software: Tools like Tableau or Power BI can be used to create interactive dashboards that allow users to explore asset condition data.

Appendix 2 Understanding the technology to support D3.1 scoring

Technology (1-2 paragraphs with ref. to WP1 technology database): and (solution ID acc. to technology database)
Description…

Relevant technical references
[1]

Purpose
Gap to close: **Relevant imperative**: **Performance indicator**: **Technical parameter**:

T 3.1 Measurement technology characteristics :		**Comments**
Spatial coverage level of the technology: - **Local component:** e.g. strain at a gauge, pot hole - **Structure:** e.g. bridge mode shapes characterized through accelerometer data, pavement project level - **Network:** e.g. load distribution captured by Weigh-in-Motion station, traffic flow on network		
Technology Readiness Level		
Need for additional data		
Alternative technologies, or technology already implemented in your AM system and provide the same information (overlap)		

T 3.2. Assessment of associated data analysis		Comments
Description of analysis		
Need for raw data interpretation		
Does the technology come with a data analysis engine and of what type is the analysis engine?		
Uncertainty of analysis results.		
Complexity of analysis		

T.3.2 Assessment of associated data representation		Comments
Overall data visualisation approach		
Does the technology come with pre-defined visualisation platform/support?		
Data visualisation supports/platform Proposal of alternative state of the art platform to improve output data interpretation		
Typical measurement frequency		
Number of measurement points		
Can visualisation data be extracted?		
Does the visualisation provide information of current state and prognosis		
Does the visualisation provide clear information for decision support		

T.3.4 Potential for practical decision-making		Comments
Is data quality sufficient for decision-making?		
Is data acquisition frequency sufficient for decision-making.		
Can (processed) measurement be directly used in decision making process?		
Advantage / Disadvantage		

T.3.3 Assessment of data integration into existing data architecture:		Comments
Data sources		

Storage methodology		
Database technology		
Data manipulation processes (validation, integration in exist. data architecture)		
Determine relevant data interfaces		
Cloud-based data processing pipeline and infrastructure for data operations		

Appendix 3 Understanding the technology: Acoustic emission

Technology (1-2 paragraphs with ref. to WP1 technology database): Acoustic sensors (solution ID 6)
Acoustic sensors that capture the elastic waves generated by concrete cracking, corrosion and other material changes such as wire ruptures. Advanced data processing is required to interpret the raw signals, which are acquired at high sampling frequencies.

Relevant technical references
[1] Structural Health Monitoring in Civil Engineering, CIRIA report, London (UK) 2020. ISBN: 978-0-86017-893-4 [2] *Surveillance acoustique des câbles. Les collections de l'Ifsttar (2015, France).* [3] *Surveillance acoustique des câbles: Guide méthodologique du système CASC – LPC – D.Bruhat, L. Gaillet et al. Techniques et méthodes des laboratoires des ponts et chaussées, Guide technique ACOUSCAB – 35p- 2012.*

Purpose:
Gap to close: Internal and remote detection, early-age damages like microcracking **Relevant imperative**: B - Reliability (Bridge Condition Index, BCI) **Performance indicator**: Cracks, corrosion, wire breaking **Technical parameter**: arrival times, energy and frequency

T 3.1 Measurement technology characteristics :		**Comments**
Spatial coverage level of the technology: • **Local component:** e.g. strain at a gauge, pot hole • **Structure:** e.g. bridge mode shapes characterized through accelerometer data, pavement project level • **Network:** e.g. load distribution captured by Weigh-in-Motion station, traffic flow on network	Local behaviour captured.	Sensor resonant frequency controls range of detection and associated noise floor.
TRL	7	
Need for additional data	Environmental data is beneficial to fine tune data processing algorithms to process acoustic data to distinguish environmental effects form deterioration. For instance, in stay monitoring for wire break detection, precipitation data (e.g. rain and grail) is measured to check	

	their impact do not induce signals that may be interpreted as wire breaks (false positives)	
Alternative technologies or technologies which is already implemented in your AM system and provide the same information (overlap)	Depending on the deterioration mechanism under consideration, Non-Destructive-Tests (NDT) may be needed to complement / confirm the outcome from acoustic monitoring (which in general only provides incremental information since system commissioning). Example of such tests are magnetic test, ultrasonic tests for cable condition assessment.	

T 3.2. Assessment of associated data analysis		**Comments**
Description of analysis	Triangulation of time of arrivals, frequency content, etc.	
Need for raw data interpretation	Yes. Advanced analytics to locate origin of signals and classify signals into relevant deterioration (crack process, wire break, etc)	
Does the technology come with a data analysis engine and of what type is the analysis engine?	No, Some specialist companies have developed their own analysis engine. However, this does not remove the need for very specialized staff to perform the analysis.	
Uncertainty of analysis results.	Analysis are associated with a degree of uncertainty arising from signal signatures, which are specific to the application case (e.g. a given cable of a given bridge subject to a given environment). Therefore, site trials are needed to calibrate the analysis. They may consist of simulating signals to characterize acoustic propagation paths. For some application (e.g. wire break detection), controlled wire ruptures may be induced to characterize actual signature	

	of signals and determine data analysis strategy.	
Complexity of analysis	Complex; specialist companies needed not only for installation but especially for data interpretation. Calibration of analysis needed to account for field conditions (see above point). It is noted that automatically detected events need manual interpretation as part of the data analysis process.	

T.3.2 Assessment of associated data representation		**Comments**
Overall data visualisation approach	Adhoc plots describing origin and frequency of identified acoustic events.	
Does the technology come with pre-defined visualisation platform/support?	No	Not in general – needs to be developed for each application.
Data visualisation supports/platform. Proposal of alternative state of the art platform to improve output data interpretation	Missing – not included	BIM can be used to show origin of identified acoustic events, as well as temporal evolution.
Typical measurement frequency	High sampling frequencies from kHz to MHz needed.	Data retention thresholds can be defined to process only relevant data, thereby minimizing data storage requirements.
Number of measurement points	Depends on application; may be high depending on case-by-case. For instance, identification and location of wire breaks along an external longitudinal post-tensioning tendon may require ca. 4-5 sensors per tendon. This quantity may be reduced if the location requirement is relaxed (e.g. if areas of corrosion risk are known in advance, for instance for lower anchorages of parallel strands stay cables).	
Can visualisation data be extracted?	yes	

Does the visualisation provide information of current state and prognosis	No	This need to be developed
Does the visualisation provide clear information for decision support	No	This need to be developed

T.3.4 Potential for practical decision-making		**Comments**
Is data quality sufficient for decision-making?	It depends on site trials generally required to calibrate the system layout and sensor characteristics. Reliability of the system in terms of false positives/negatives rates is needed to inform decisions.	
Is data acquisition frequency sufficient for decision-making.	Yes. Acoustic monitoring needs high sampling rates (from kHz to MHz). Near real-time monitoring is possible to signal the occurrence of events.	
Can (processed) measurement be directly used in decision making process?	Yes, e.g. to inform areas to focus inspection and/or testing and to inform maintenance and repair plans.	
Advantage / Disadvantage	Advantage: Real-time incremental condition assessment of hidden defects (e.g wire breaks of post-tensioning tendons). Disadvantage: false negative/positive rates; need to correlate results with other assessment methods.	

T.3.3 Assessment of data integration into existing data architecture:		**Comments**
Data sources	Raw data files containing acoustic signals	Describe what data is coming
Storage methodology	Local DAUs and then cloud via ftp server	Describe + how it can be integrated
Database technology	SQL	Describe + how it can be integrated

Data manipulation processes (validation, integration in exist. data architecture)	Data validation shall be performed by specialist companies as part of the commissioning process and site trials to inform data analysis. Regarding integration with existing data architecture, this is not always required, and it depends on whether the acoustic monitoring is deployed temporally (to assess existence/absence of an issue) or permanently as part of a wider instrumentation. For the latter, transmission and integration of raw data files and processed outcomes (e.g. wire breaks) shall be treated separately. The processed outcomes can be integrated within a permanent data infrastructure containing e.g. data from other sensors.	Describe requirements
Determine relevant data interfaces	API with acoustic monitoring specialist is needed to process raw data and retrieve processed data only	via e.g. restful API
Cloud-based data processing pipeline and infrastructure for data operations	Automated pipeline possible up to a degree; manual verification by acoustic specialists required.	Describe