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INFRACOMS

Innovative and Future-proof Road Asset Condition Monitoring Systems

Integration of New and Emerging Technologies into Data Architectures

Deliverable D3.2

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Belgian Road Research Centre
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Project acronym: INFRACOMS

Innovative & Future-proof Road Asset Condition Monitoring Systems

Report D3.2

Integration of New and Emerging Technologies into Data Architectures

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Abbreviations

Abbreviation	Definition
AE	Acoustic Emissions
AI	Artificial Intelligence
AR	Augmented Reality
BDOA	Base de Données des Ouvrages d'Art
CEDR	Conference of European Directors of Roads
INFRACOMS	Innovative & Future-proof Road Asset Condition Monitoring Systems
GIS	Geographic Information System
HDM4	Highway Development and Management Module (version 4
LiDAR	Lig Distance and Ranging
NRA	National Road Authority
TRL	Technology Readiness Level
VR	Virtual Reality
WP	Work Package

Executive summary

INFRACOMS is a CEDR Transnational Road Research Programme Call 2022 project (June 2022 – May 2024), aiming to understand current and emerging remote asset condition monitoring and data collection techniques, to enable European National Road Authorities (NRAs) to strategically implement innovative technologies and approaches as standard practice. It has a specific focus on two primary asset types: road pavements and bridges.

The INFRACOMS project encompasses five work packages, labelled WP1 through WP5. This document, D3.2, is a deliverable of WP3. At the point when this report is written, WP1 had already reached completion. This segment involved an extensive review of the current practices in asset health monitoring, the requirements of National Road Authorities (NRAs), as well as the identification of existing gaps that need to be addressed. Meanwhile, WP2 is in progress. It focuses on developing an appraisal methodology for the technologies. This process of appraisal comprises two parts: a pre-evaluation phase and a subsequent evaluation phase.

WP3, the work package to which this report contributes, represents a critical part of the appraisal phase. During this stage, technologies are appraised based on a variety of factors. These factors include the data analysis and visualisation, its integration into the existing data architectures, and its potential for practical decision making.

The initial report in this work package, namely D3.1, proposed an approach to appraise technologies according to the first two factors: data analysis and visualization. Building upon that, this report D3.2 proposes an approach to appraise technologies for the remaining factors: the integration into existing data architectures and their potential for decision making. Collectively, these two reports develop am appraisal/ scoring system for technologies considering all the above factors.

To appraise the ability to integrate the data provided by a specific technology into an existing data architecture this report commences with the development of an approach to describe the “ideal” data architecture, that can integrate various types of data from new and emerging technologies to facilitate decision making. The data architecture forms a pipeline from raw data creation/delivery to data ingestion, data organization, data analysis and visualisation, until information that is useful for decision making.

We then review two existing data architectures as examples in the context of the proposed data architecture pipeline. From the understanding of the two sides – the data properties of technologies and the capabilities of data architectures – we develop an appraisal scoring process to evaluate the ability to integrate the new data into the existing data architecture. To generalize this approach, the report presents a list of questions that can be used by stakeholders to help understand the data architecture used by any NRA (not only limited to the selected examples) when conduct the appraisal. We also develop an appraisal scoring process to evaluate the potential of the technologies to support practical decision making.

The outcomes in this report (D3.2) and the previous one (D3.1), complete the INFRACOMS appraisal (scoring) system for the aspects of: data analysis, visualisation, integration into data architecture and potential support for decision making (forming part of the overall appraisal process). An example application of the process is presented for the case of acoustic emission monitoring the wire break in steel cables. In addition, the process has been applied to further technologies in the INFRACOMS database 1.0, and provided in the appendix. It is anticipated that refinement, and further guidance in the application of the process, will be developed when it is applied to the case studies in WP4.

Glossary

Table 1 summarises the terminology used throughout this document.

Table 1. List of terms and meanings.

Term	Meaning
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)
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)
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.

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.

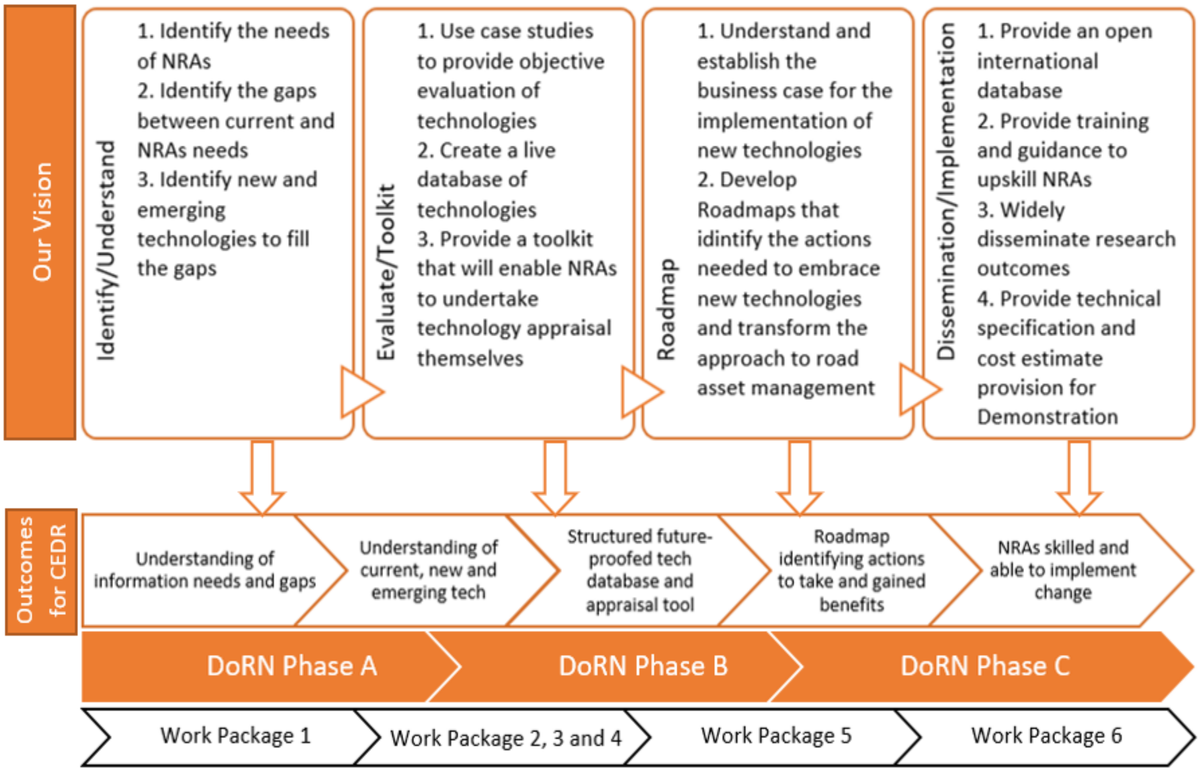

Figure 1. Vision and outcomes of INFRACOMS.

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 (D3.2 – Integration of new and emerging technologies into data architectures) 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.

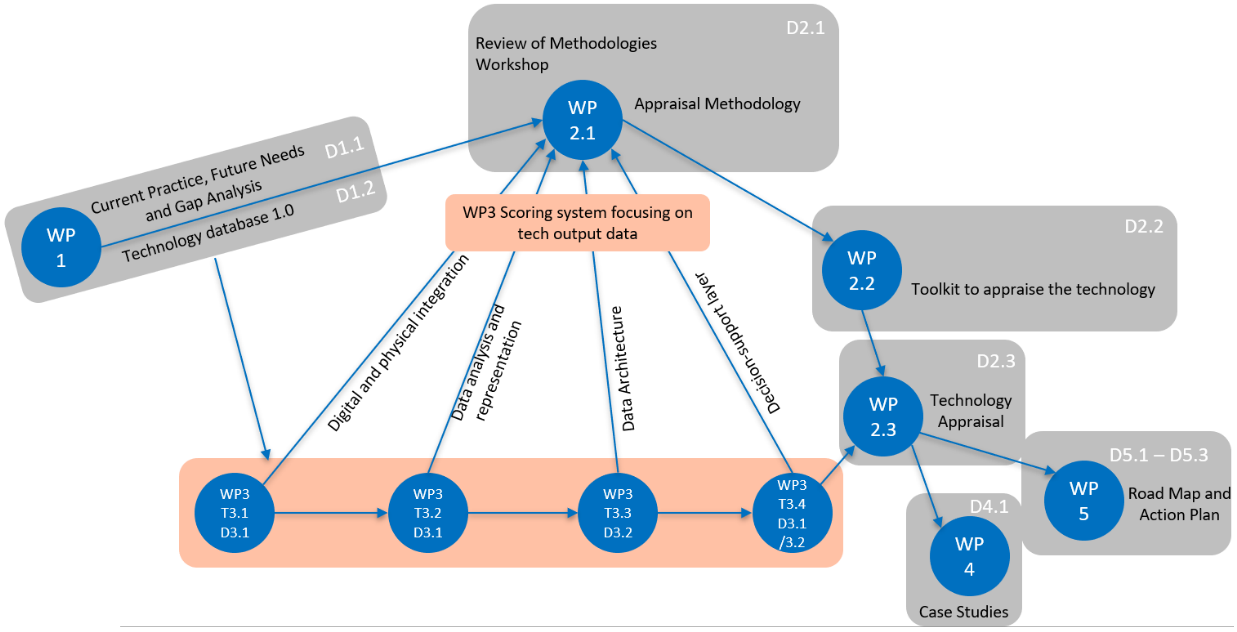

Figure 2. Relationship of WP3 to other Work Packages, Tasks and Deliverables

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 delivered D1.2 – which contains the INFRACOMS Technology Database 1.0. This contains a list of remote condition monitoring technologies which are mapped to current and future asset management needs / use cases identified in the consultation carried out in WP1. This Database is utilised within this WP3 report.

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.

The first deliverable from WP3, D3.1, reviewed and evaluated the data output from the technologies contained within the Technology Database 1.0. It discussed the data provided by specific technologies and how these data can be related to actual physical assets. In addition, it was discussed how the data output would provide value in terms of identifying the performance of an asset. A particular focus of D3.1 was on how the data should be analysed and visualised to provided optimal value.

This report, D3.2, serves as the second and final deliverable from WP3. It presents the data architecture considerations for incorporating the data provided by technologies into asset management systems. In addition, it provides an approach to evaluate the potential of a particular technology to support decision-making. Ultimately, in conjunction with D3.1, WP3 establishes an appraisal system that assesses a technology's capacity to offer value through data analysis and visualisation, and the ability to integrate the data provided into existing data architectures.

INFRACOMS WP2, carried out in parallel with WP3, will develop a toolkit to implement the appraisal methodology as part of WP2.2. 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 provide a user manual.

WP4 will develop real-world case studies for the most promising technologies identified using the appraisal 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 Overview of WP3

The work described in this report was carried out under WP3. WP3 supports the "Evaluate/Toolkit" step of INFRACOMS, by considering the "end-to-end" requirements of the technologies that will be appraised via the INFRACOMS toolkit. This includes the interpretation and visualization of the data provided by a technology, the integration of the data into existing data architectures and the potential of the data to support practical decision making.

The objectives of WP3 are:

- To assess 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 the 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)

The first two objectives were addressed in the deliverable D3.1, and the remaining two will be addressed in this report.

1.4 Scope of this report (INFRACOMS Deliverable D3.2)

This report evaluates the integration of data from new technologies into data architectures, and the potential to support practical decision making. First, we provide a definition of data architecture, in the context of the use of data with the asset decision-making purposes (Section 2). We then present an INFRACOMS data architecture model to ingest data from new technologies. In Section 3, we review two existing data architectures currently employed by NRAs. Based on the observations from these existing data architectures, we assess the ability to integrate data from new technologies into existing data architectures. In Section 4, we present a system for appraising the ability to integrate data from a new technology into existing data architectures and to appraise its potential to support practical decision making. These, together with the data analysis and visualization appraisal presented in D3.1, complete the appraisal system. The appraisal process is applied to the technologies above TRL level 7 (contained within INFRACOMS Database 1.0), and the summary results provided in an appendix to this report.

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. 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 may 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 of expertise. However, the toolkit will not prevent the assessor from undertaking a wide-ranging appraisal if desired.

2. A generic description of data architectures

Data architecture refers to the overall design and structure of an organization's data assets, including databases, data models, data integration processes, data storage, and data management practices. It provides a blueprint for how data is collected, stored, organized, processed, and used within an organization.

In the context of INFRACOMS, it describes how asset data is managed from collection, through to ingestion, analysis and visualisation.

As emerging technologies, like the Internet of Things (IoT), introduce new data sources, a robust data architecture ensures that data remains manageable and valuable, facilitating data lifecycle management. In particular, it can prevent redundant data storage, enhance data quality through cleansing and avoiding duplication, and enable the development of new applications.

2.1 INFRACOMS data architecture model

To provide context to the concept of data architecture we describe a generic data architecture, which encompasses most of the architectures that would currently be used by NRAs, in Figure 3. This generic data architecture includes the following segments:

- Data collection (inclusive of Metadata, Technology, and Data Source)
- Data ingestion and storage (inclusive of Data Ingestion, Data Ontology, and Data Storage)
- Data consumption (inclusive of Data Analysis, Data Visualisation and Decision Making).

Each of these segments is discussed in detail in the following sections.

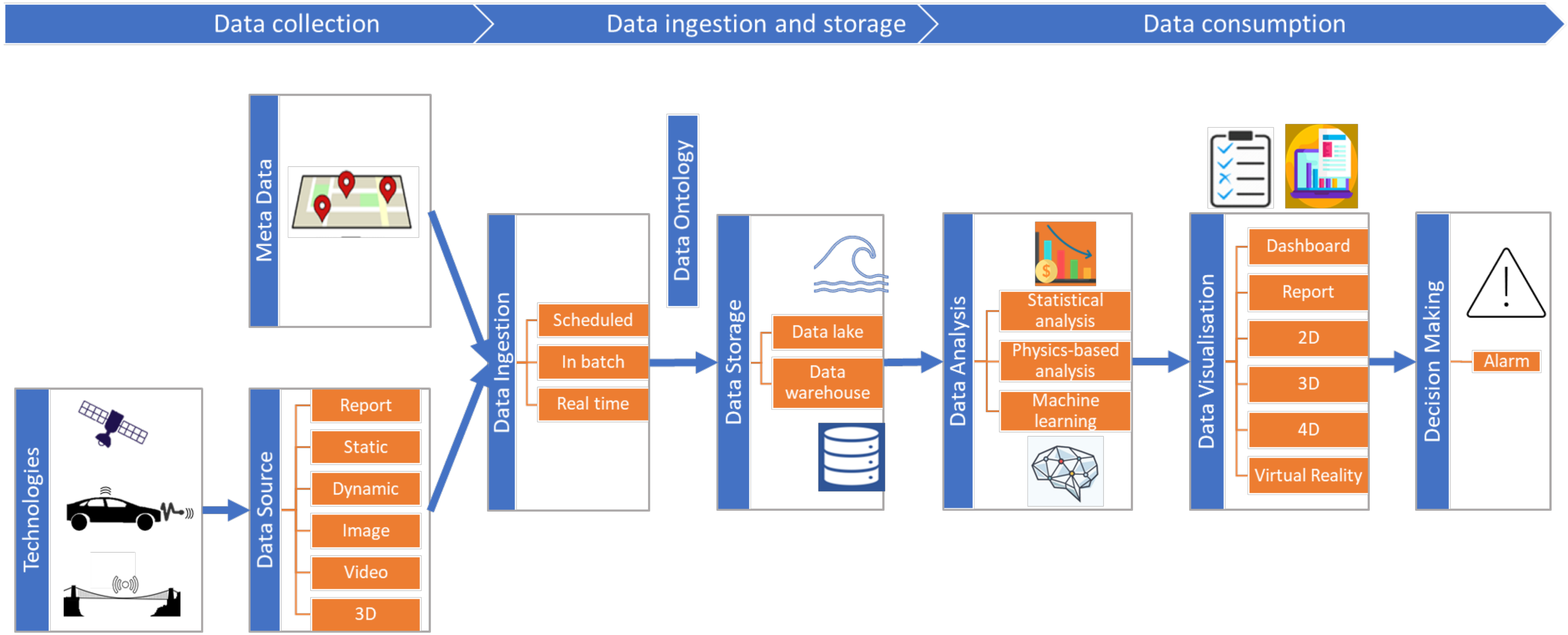

Figure 3 The generic INFRACOMS data architecture model

2.2 Data collection

The generic architecture begins with data captured by the technologies. A review of technologies included in the INFRACOMS Technology Database 1.0 (those with a TRL level exceeding 7), has shown that these new technologies typically generate data types that can be defined as report, static data, dynamic data, images, videos, or 3D data. Definitions and some examples of these data types are given in Table 2.

The categorization of data types is established based on the monitoring needs and the capabilities of emerging technologies, as identified through literature reviews and interviews with NRAs. These data type groups may overlap; for instance, video data, as a time-lapse sequence of images, is also considered dynamic data. Hence, the data produced by a particular technology can fall into multiple categories.

The reason of discussing data types lies in the development of new technologies and the evolving needs for asset monitoring, which consequently generate novel data types. These new data types require enhancements of the data architecture to facilitate their integration. Therefore, an ideal future data architecture should possess the capability to accommodate these emerging data types.

Alongside the data from technologies, metadata - comprising details about the measurements such as time, location, and the individual responsible – are also integrated into the system.

Table 2 Data types from the technology examples in database 1.0 with TRL level above 7.

Type of data	**Description**	**Examples in INFRACOMS Technology Database 1.0 with TRL over 7**
Reports	A report is a document that presents information in an organized format for a specific audience and purpose. (Wikipedia, 2023)	Many technolgoes allow exportation of data in reports format, such as xx
Static data	Static data structures are designed to store static set of data that the memory size allocated to data is static. It is possible to change the content of static data but without increasing the memory space allocated to it. (Computer Science Wiki, 2017)	Typical static data are measurements at a scan, like crack pattern.
Dynamic data	Dynamic data or transactional data is information that is periodically updated, meaning it changes asynchronously over time as new information becomes available (Wikipedia, 2023).	Acoustic Emission Instrumentation of a cycle path (InfraLytics) Fibre optical sensors
Images	An image is a 2D representation of an object.	EyeVi Platform - point cloud generation COWI virtual inspection platform
Videos	Video is an electronic medium for the recording, copying, playback, broadcasting, and display of moving visual media (Wikipedia, 2023).	Video Camera-based Structural Health Monitoring-Motion magnification
3D data	3D data is an 3D representation of geometric	LIDAR

	data. Contrary to what the name suggests, 3D data are most often displayed on 2D displays. In virtual reality systems, 3D data can be displayed in 3D (Wikipedia, 2023).	Instrumentation of a cycle path (InfraLytics) COWI virtual inspection platform

2.3 Data ingestion and storage

Data ingestion is the process of importing or loading data into a database, data lake, or data warehouse for immediate use or storage. This data can be ingested at scheduled timing, in batches or streamed in real time:

- At scheduled timing: only the data at certain timing can be integrated into the data architecture. For example, the ingestion is scheduled every month and takes 1 hour. Only the data at that hour is ingested.
- In batch: the data is also ingested at scheduled timing, but this includes the complete data in the period between the current and previous ingestion timing. Taking the same example that the ingestion is scheduled every month, in this case, all the data collected in the month are batched and ingested at once.
- In real time: the complete data can be integrated into the data architecture in real time, e.g. data once generated is uploaded to the cloud immediately.

To facilitate data ingestion, data ontology or organization is typically employed. This process involves organizing the data according to a specific set of rules to enable efficient integration. The organization can be according to the metadata (e.g. time and location of the measurement), the type of data source (e.g. static, dynamic, images and etc.), or the parameter that the data represents (e.g. displacement, crack, friction and etc.).

Once organised, the data is stored in a data lake, and categorised in a process known as data warehousing, which allows for structured search and analysis later on. Until this point, the data content has not been analysed, rather, it has been organised for more effective interpretation in the subsequent stages.

2.4 Data consumption

Data consumption includes data analysis, visualisation and informed decision making. Each of these components is explained in the following paragraphs.

Data analysis is performed based on specific needs, using methods such as statistical analysis, physics-based method, and/or machine learning method.

- Statistical analysis extracts meaningful insights from large amounts of data and predict future trends, or to make informed decisions considering the uncertainties.
- The physics-based method assumes that a physical model, accurately describing the phenomena behind the data, is available. This approach interprets data in a physical context, allowing for understanding and prediction of future behaviour.
- The machine learning method utilizes data to discover unknown underlying relationships, enabling prediction of future outcomes. This approach requires substantial amounts of data to effectively train the models.

Following analysis, data are visualised to ease the decision making. The data could be represented by dashboard, in report format, in 1D, 2D, 3D or 4D, or through visual reality (VR).

- Dashboard is a tool to visualise the performance indicators for a quick and easy understanding of the data.
- Report, 2D and 3D visualisation can refer to the definitions in Table 2.
- 1D visualisation refers to a visualization method where data are represented on a single dimension or axis. The common forms of 1D visualization are histogram, line graphs, bar charts, or pie charts.
- 4D visualisation refers to a way of representing data in four dimensions. In most cases, these four dimensions are three spatial dimensions (width, height, depth) and one temporal dimension (time).
- VR visualisation is the process of creating a simulated 3D environment using computer technology. Users typically wear a headset that tracks their head movements and displays a 3D world to their eyes.

Based on the data analysis and visualisation results, alarms can be given to the asset owners to decide the interventions to be taken (decision-making). Depending on the monitoring results, decisions on asset management could be of different levels. For road asset management, the decisions can be at levels of network level, scheme level and operations level:

- Network level: decisions which affect the entire network such as deciding maintenance budget and national speed limit
- Scheme level: decisions regarding planned maintenance and construction
- Operations level: day-to-day decision making such as traffic management responding to incidents and asset failures.

For bridge asset management, the decisions can be at levels of global structural level, local structural level and non-structural level:

- Global structural level: decisions which affect the global safety of the bridge. Consequence is on collapsing of the bridge, such as decisions regarding the severe scour of middle pier that endangers the global structural safety of bridge.
- Local structural level: decisions that affect the serviceability of the bridge. Consequence relates to serviceability of the bridge components but will not result in collapsing of the bridge, such as decisions regarding the heavily damaged expansion joint which can potentially result in partial closure of the bridge (limits its serviceability).
- Non-structural level: decisions that affect the utility of the bridge. Consequence relates to the daily usage of the bridge, such as decisions regarding the non-structural elements of the bridge (such as railing, drainage system, markers on pavement, lights…). .

3. Existing data architectures used by NRAs

3.1 Approach

To understand the requirements/implications of integrating the data provided by a new technology into an existing data architecture, it is necessary to understand the framework of that data architecture. In this chapter we illustrate this using real-world examples - one focussing on road asset management, and the other for bridge asset management.

When assessing/understanding the capabilities of an existing architecture it is useful to take a formalised approach that considers each of the components shown in Figure 3. Therefore, a set of questions was developed to help stakeholders document and understand data architectures that may be found in asset management systems used by other NRAs, as shown in Appendix A. The questions are formulated according to the stages in data architectures as described in Section 2. Based on responses to these questions, stakeholders should be equipped to assess the potential integration of a technology into a specific data architecture in use in a NRA. For the systems discussed in this chapter, INFRACOMS discussed the architectures with users/developers of those systems, in the light of this set of questions.

3.2 Existing data architecture for road management: The iROADS system

iROADS is an asset management system implemented to address the specific needs of National Highways (NH) in England to facilitate management of the data associated with motorway and trunk road assets (TRL software, 2021). The aim is to optimise the performance, condition, and lifespan of these assets while ensuring the efficient use of available resources. The aims of NH's asset management process, which iROADS supports, include:

- Maximising the use of data and digital technology
- Standardising asset management processes
- Developing a whole life cost approach
- Managing asset risks effectively
- Enabling net zero commitments
- Maturing the asset management capability
- Embedding asset management

iROADS is a Commercial Off-The-Shelf (COTS) product that has been customised and calibrated for NH. It includes a number of optional modules that can be enabled or disabled, depending on the needs of the client. iROADS has the ability to store data in a wide range of georeferenced formats. Information can be summarised and presented via dashboards.

3.2.1 Data ingestion and storage

Data in the NH implementation of iROADS is stored on the cloud. The details of information stored in iROADS is shown in

Table 3.

Table 3 Data / information stored in iROADS

Concept	Description
Identification	Includes assigned road number, road name, start and end points, georeferenced location, etc.
Information	Network data, asset data, asset survey data, query by attributes, GIS integrated solutions
Management	Includes the responsible body
Pavement	Includes surface type, surface age, and information on pavement structure (where available)
Maintenance and management system	Define treatments and lifecycle, work programme and budget, Prioritisation, whole life costing and lifecycle planning, works programmes
Geometry	Horizontal and vertical
Mobile data collection	Mobile app to collect asset condition, search and survey forms
Condition	Imports and displays condition survey data – including surface and structural condition data
Photos	Allows the storage of deposited snapshots generated during inspection reports Using the road vision feature, users can view the survey imageries as video along with the condition data
Documents	Allows the storage of all types of documents related to the road
Mapping	Can import various types of background map, i.e. OSM, satellite, Google Earth etc. Can import spatial data from external systems and use it in iROADS for querying and analysis
3D view	Has the ability to view maps in 3D
HDM4	Has a built-in link to HDM4 (the Highway Development and Management Module), data is readily transferrable both ways
Public Mobile App	Search/view asset summary information, raise alerts by specifying asset issue and location, track status of grievance Public dashboard for the public to view the reported issues with performance indicators
Bridges	Upload and manage data, set up inspections, Bridge condition index, store specific reports
Traffic	Location of traffic survey stations, traffic count data, axle load data and traffic modeling
Cloud or server based	The RAMS can be set up as a cloud-based option or can be installed on a local server. Preferences can be applied so that different users has different levels of access, based on the priorities of the user.
GIS	Mapping/GIS functionality is built into the interface

3.2.2 Data consumption – Visualisation tools

Mapping/GIS functionality is built into the interface. It can link to various types of mapping and map servers, including open-source maps such as Open Street Map (OSM), GIS vector and raster data (Figure 4). Google tools such as Google maps, Google Street View, and Google Earth can also be included in the iROADS interface providing that the license is available to the client. All data can be displayed in the map interface. iROADS also has the capability to show a 3D view of mapping, as shown in Figure 5. The base layers can include point, linear and polygon data, as shown in Figure 6. Any data held in iROADS can be displayed on the map interface, as shown in Figure 7. There are also visualisation tools for condition and defects, which can be displayed together as shown in Figure 8.

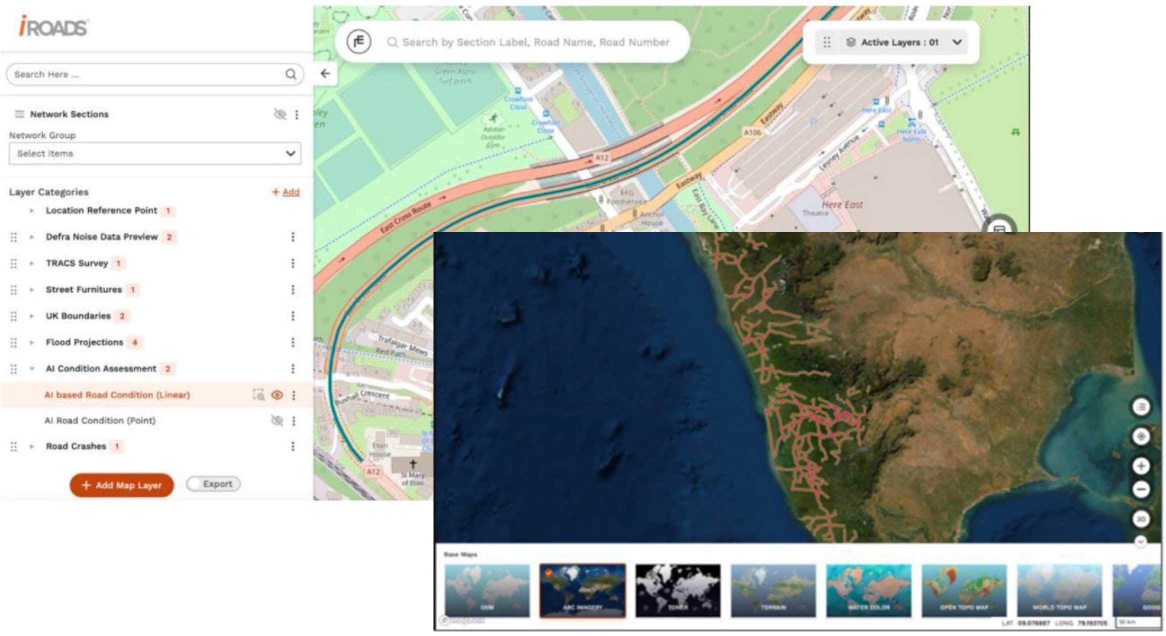

Figure 4: iROADS background mapping options

Figure 5: iROADS capability for 3D mapping

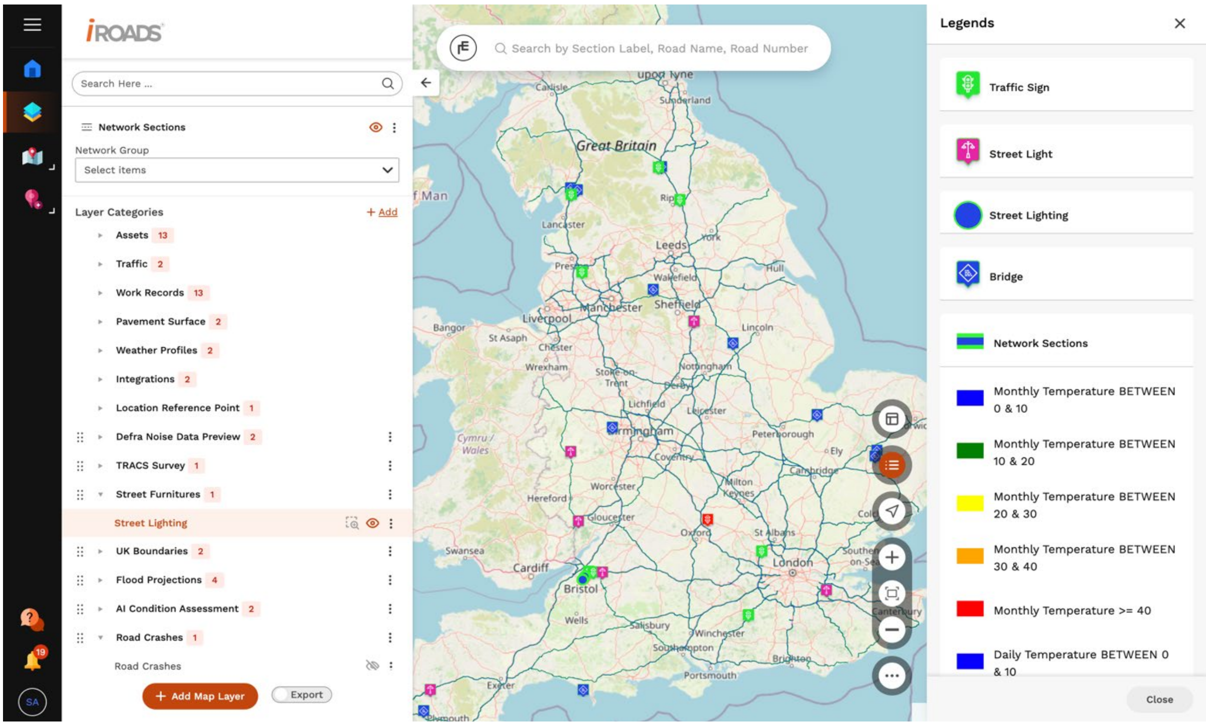

Figure 6: iROADS inventory information layers

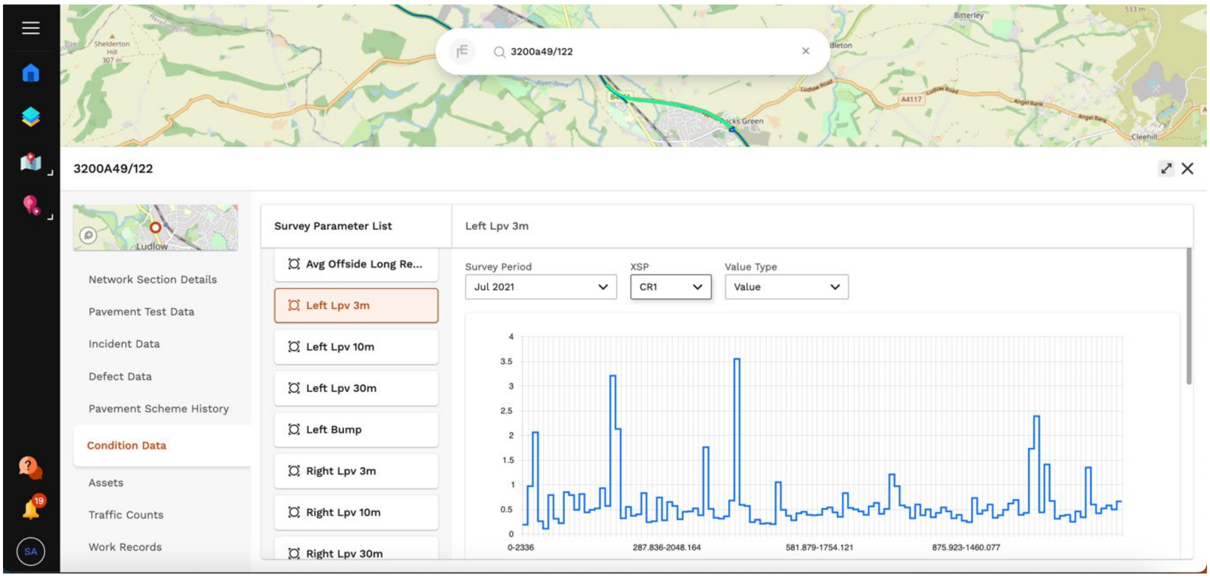

Figure 7: iROADS visualisation of condition data

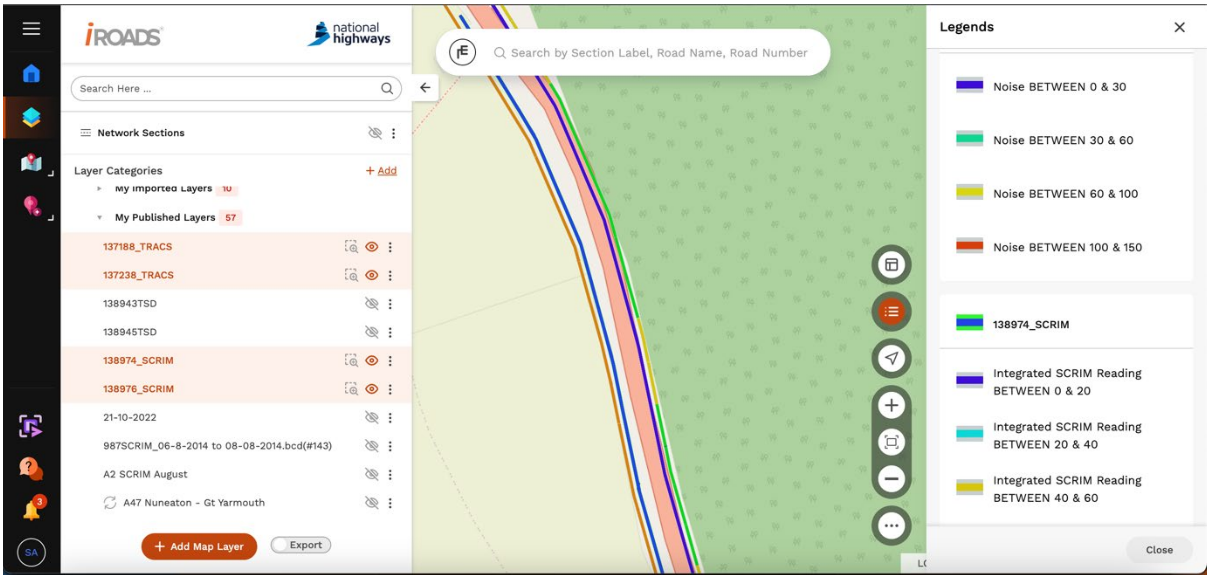

Figure 8: iROADS detailed visualisation of multiple conditon data sets

3.2.3 Data consumption – Analysis tools

Analysis of Condition

iROADS is able to process different categories of condition data, with the visualisation being shown in Figure 9. In this particular example the KPI for National Highways in UK uses only Good and Poor categories for condition, but iROADS can define any categories, including a RAG (Red, Amber, Green) system.

In terms of condition monitoring iROADS has a KPI dashboard that facilitates national target setting, with a monthly dashboard, KPIs, targets and 12-month average, Future KPI for new defects and network analysis.

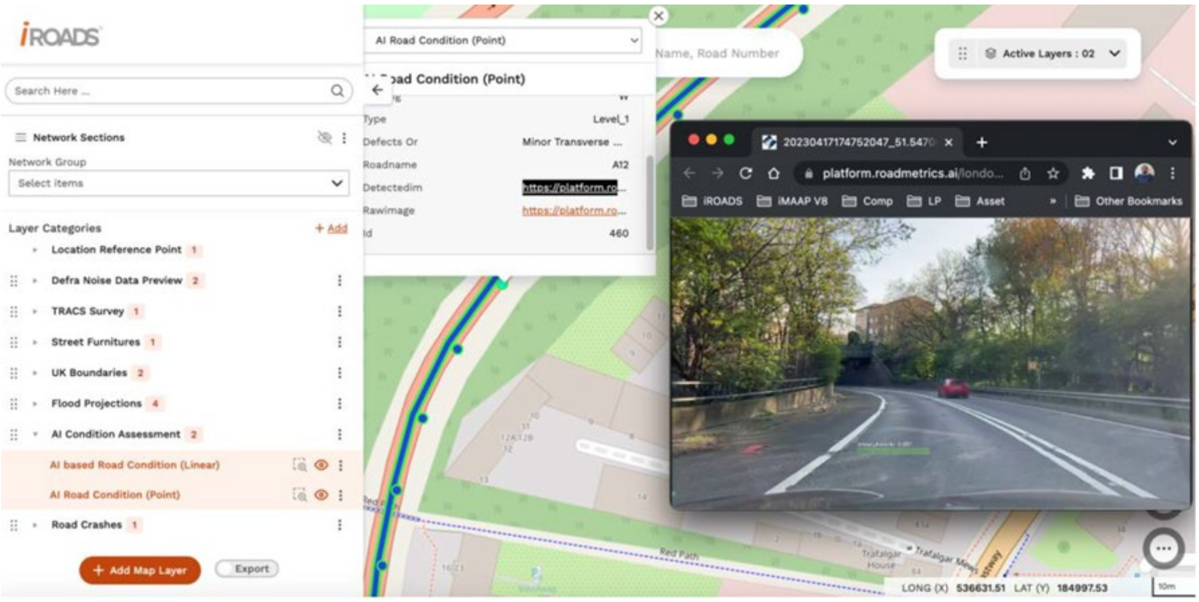

Figure 9: iROADS visualisation of road condition data

Analysis of network performance:

iROADS can carry out network analysis for multiple years, budget constrained, and condition constrained, and produces a forward works programme for multiple years based on proposed treatments, as shown in Figure 10.

iROADS also has a Whole Life Cost model and supports the value management process to evaluate schemes, considering value for money and reduction of disruption on the network. It uses treatment selection and deterioration algorithms to predict the maintenance requirements for schemes over a 60-year period, as shown in Figure 11. It also calculates Whole Life Costs and User delay costs which are used to calculate measures of Value for Money and Reduction of Disruption, for different treatment options. It also includes maintenance scheme investigation, with treatment options and prioritisation.

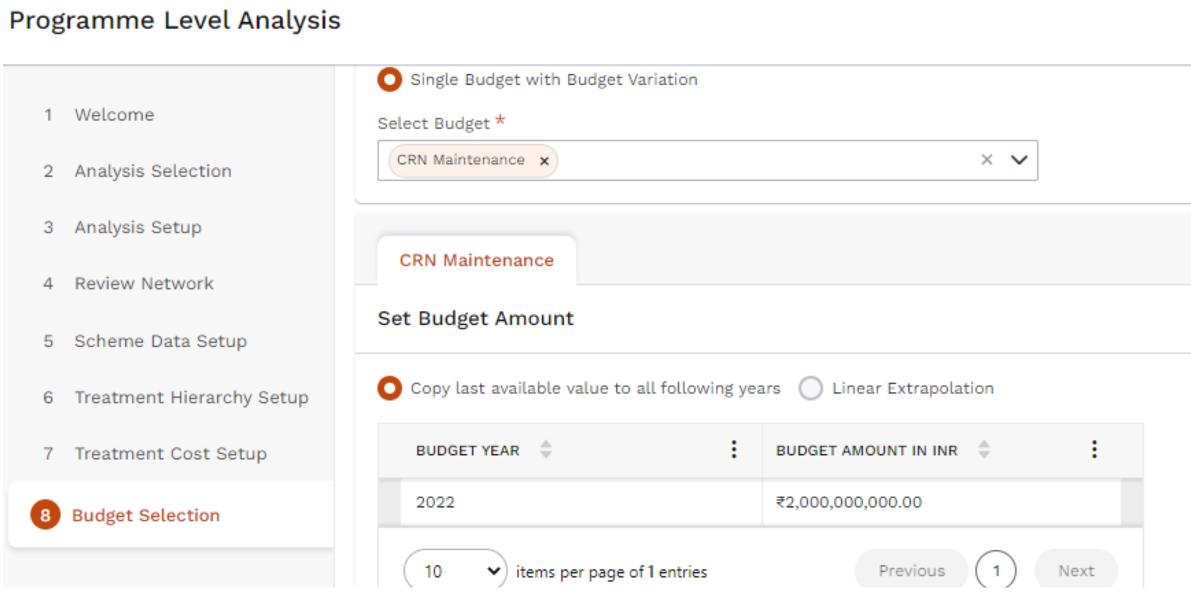

Figure 10: iROADS Programme level analysis

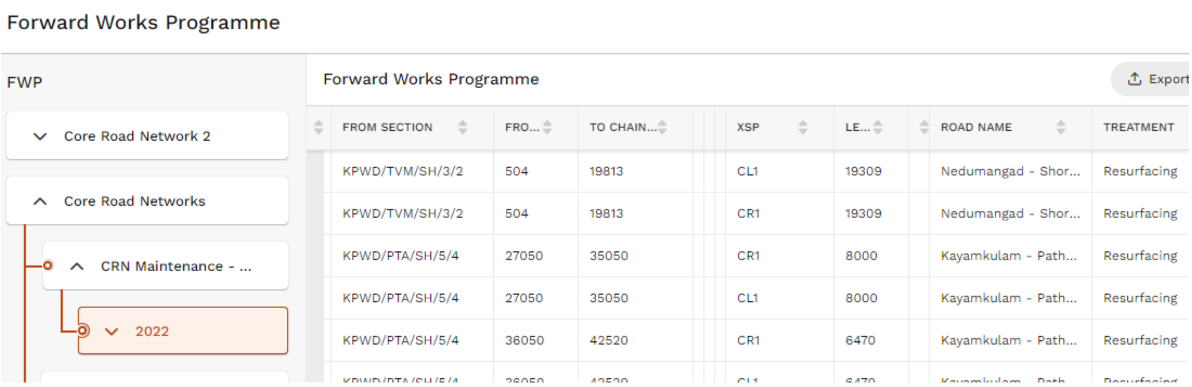

Figure 11: iROADS Forward works programme

Analysis of Traffic

iROADS has a Traffic manager module, which stores vehicle type definitions, traffic classifications and traffic count aggregations. It can apply seasonal correction factors and growth rule configurations, as well as displaying traffic layers on map, with traffic stations. iROADS can carry out advanced analysis based on traffic data, with advanced filter options based on traffic counts and axle loads. The processing and visualisation are shown in Figure 12.

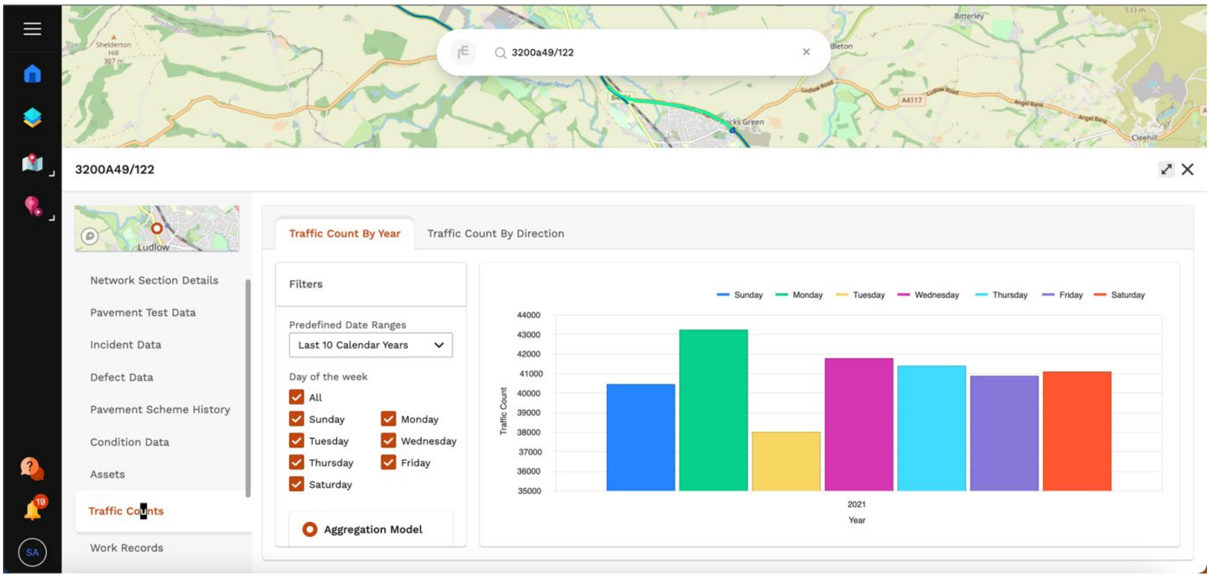

Figure 12: iROADS storage and visualisation of traffic data

Analysis of climate:

The climate module can accept climate/environmental data from various authorities. Historical and projected data can be displayed on graphs and GIS maps and it has the ability to receive, store, retrieve, visualise and analyse the different types of data for environment & climate. Environmental factors such as humidity, temperature and rainfall are considered while predicting deterioration of the road. The software can create climate zones, import historical and forecasted weather data from external sources, view weather profiles and send disaster alerts to road engineers.

3.2.4 Capabilities of iROADS within the INFRACOMS architecture model

An initial, basic assessment of iROADS in the context of the INFRACOMS generic data architecture model suggests that iROADS has the ability to meet most components of the model. It is able to ingest store and analyse a wide range of complex datasets and has a number of visualisation tools. These can be summarised as illustrated in Figure 13. From our assessment of the system, the functions not currently supported by iROADS appear to be limited to using machine learning methods within the analysis. However, this is an initial assessment based on an overview of the system. The assessment does not provide an assessment of the level of complexity that may be experienced when trying to implement new data within the system - see Section 6.

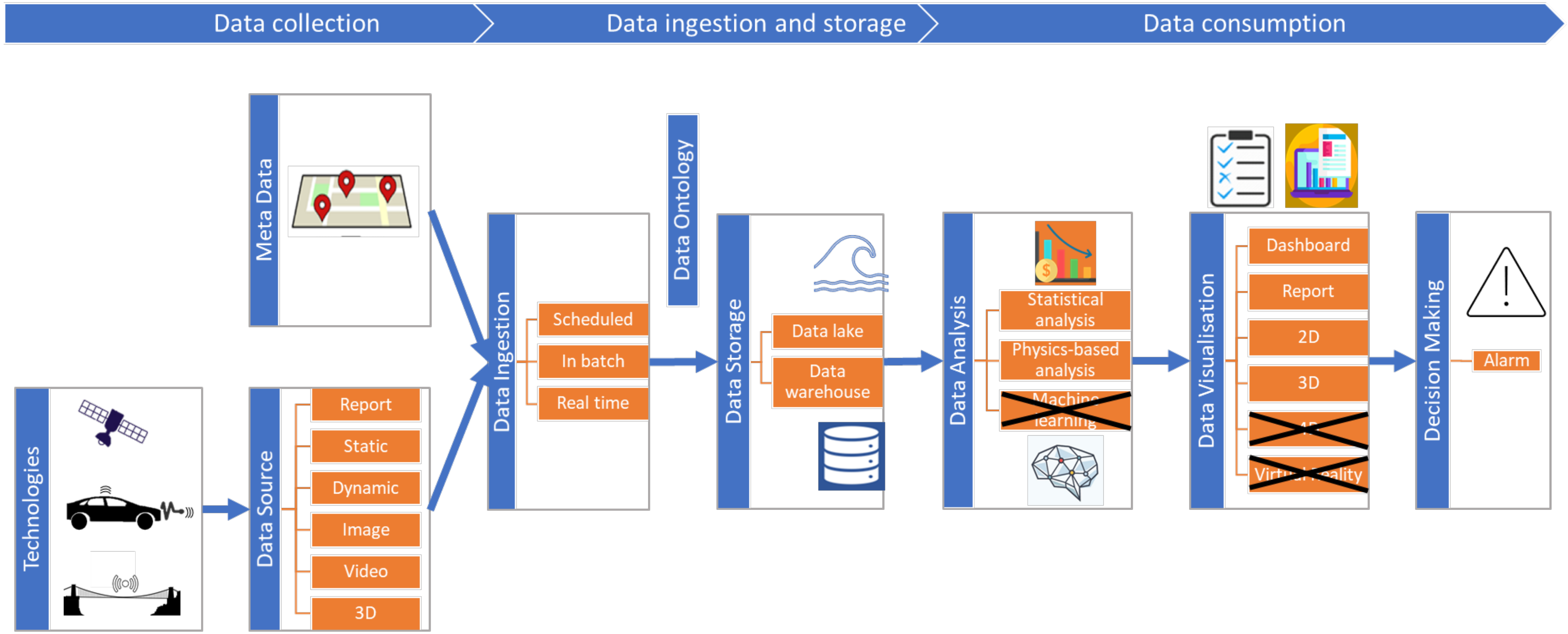

Figure 13 Reflection of the iROADS management system to the INFRACOMS data architecture model. The functions not currently supported are stroke through which is machine learning in data analysis, and 4D and VR in data visualisation.

3.3 Existing data architectures for bridge management: Wallonia Bridge Management System

Wallonia Public Service (SPW) in Belgium use the BDOA (Base de Données des Ouvrages d'Art) system to manage its bridge assets (also including other structural elements like retaining walls and tunnels). BDOA is a software product designed to address the various needs expressed by all stakeholders involved in the asset management (Wallonia Public Service, 2023). The primary objectives during the software's development were to:

- Store a diverse range of information characterizing structures
- Provide broad access to this information
- Enable structure managers to update the data through dependable security mechanisms
- Facilitate data sharing among the different stakeholders involved.

The application relies on intuitive and fast search tools for locating structures, as well as numerous screens that allow users to view and input general data about structures (such as identification, technical description, etc.) and data related to the inspections conducted on the structures.

3.3.1 Data ingestion and storage

The BDOA application for SPW has a main page as displayed in Figure 14. Various asset data is stored within the system which can be searched including identification, construction, geometry, equipment, management, templates, bearing capacity, authorizations, documents, photos, levelling, load testing, inspections, health status, repairs, interventions throughout the structures' life, mapping, and field views – see Table 4.

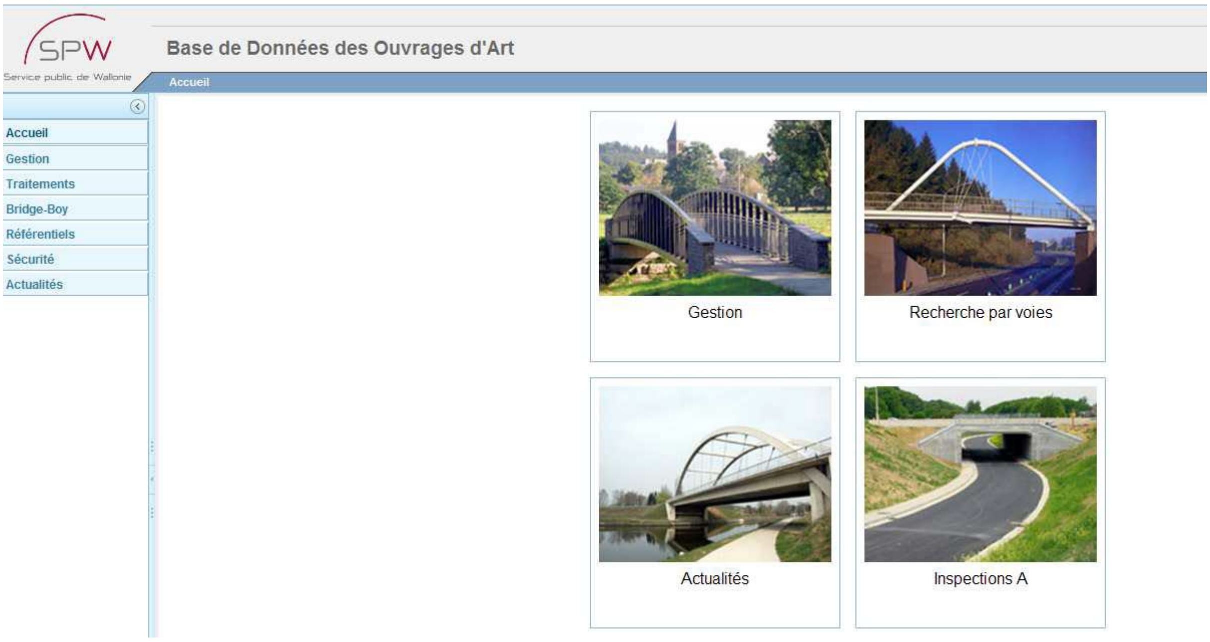

Figure 14 BDOA management system

Table 4 Description of the data included in the BDOA management system [1].

Concept	Description
Identification	Includes the following information: BDOA Number, Identification Number, Name, Location and etc.
Construction	The data related to the construction of the structure: Entity number, Decision-making entity, Type of contract, Award date.
Geometry	Lists the following elements: Type of structure (frame, beam bridge, ...), Function (canal bridge, rail bridge, …), Stability (isostatic, hyperstatic, cantilever, …), Skew angle (if any), Constituent material (steel, concrete, prestressed concrete, wood, …), Number of spans, Number of supports, Number of expansion joints, Dimensions (length, width, area) and etc.
Equipment	Includes information related to: Pavement and waterproofing layers, Types of joints, Types of supports, Possible noise barriers and etc.
Management	Describes the managing entities, especially in the case of shared management.
Template	Allows defining the templates for various axes (clear height, road width, etc.).
Bearing capacity	Provides information on the structure's bearing capacity (load bearing capacity) as well as on the calculation standard used for the construction
Authorizations	Includes any granted requests for passage of exceptional vehicles
Documents	Allows you to store all types of documents scanned (plans, authorizations, agreements, etc.).
Photos	Allows the storage of deposited snapshots either manually or automatically generated during inspection reports, …
Levelling	Includes information related to the levelling performed on the structure (presence of levelling markers, campaigns carried out, etc.).
Load testing	Concept designed for load testing. It is possible to include the test(s) carried out, possibly attaching a file to it.
Inspection A	Includes information related to type A inspections performed, as well as their frequency. It also allows for the input of a new type A inspection.
Inspection B	Includes information related to various specialized inspections (Type B) carried out on the structure, each time accompanied by the related file.
Health status	Allows assigning a health class to the structure, as well as a vulnerability level. Enables defining a periodicity for type A inspections.
Repairs	Concept under review.
Interventions	Synthesizes the work done during the intervention.
Mapping	Opens a window with an interactive map displaying the location of the structure. It is possible to display a wind rose that allows orienting the structure according to SPW conventions (upstream-downstream-left-right).
View of the field	Opens a street view window either on or under the work

Inspection data: There are two types of inspections included: Inspection A, which is performed periodically, and Inspection B, which is carried out for special purposes but not on a regular basis. The frequency of Inspection A can either be calculated automatically according to the SPW Management Regulation (3 or 6 years in most cases) or defined manually.

Sensor data: A number of bridges are equipped with sensors for condition monitoring. However, the raw data from the sensors is not stored in the management system BDOA. A separate system called the web data platform is used. Data from sensors are uploaded in real-time via FTP and the web data platform searches every 5 minutes to ingest the data.

Other data than the sensor data is stored in BDOA system (Figure 15).

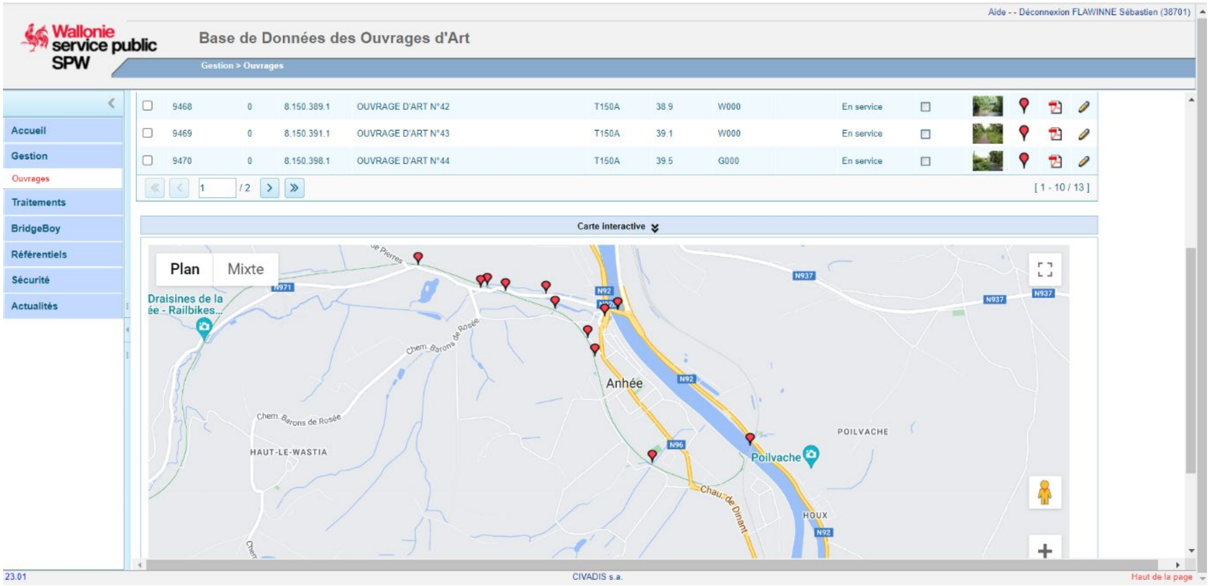

Figure 15 Bridge asset information

3.3.2 Data consumption

Consumption of sensor data including visualisation and analysis is undertaken in the web data platform. Alarms can be displayed based on the measured indicators in the form of a dashboard (Figure 16). Figure 17 shows an example of two alarms related to the strain of the rods and the inclination of the monitored wall. Users can access this platform through a link on the project page within the BDOA system. Therefore, these two systems – BDOA and web data platform – are **effectively** connected, tackling the challenges of storing large amounts of data (through the web data platform) and creating a user-friendly management interface (by utilizing the BDOA).

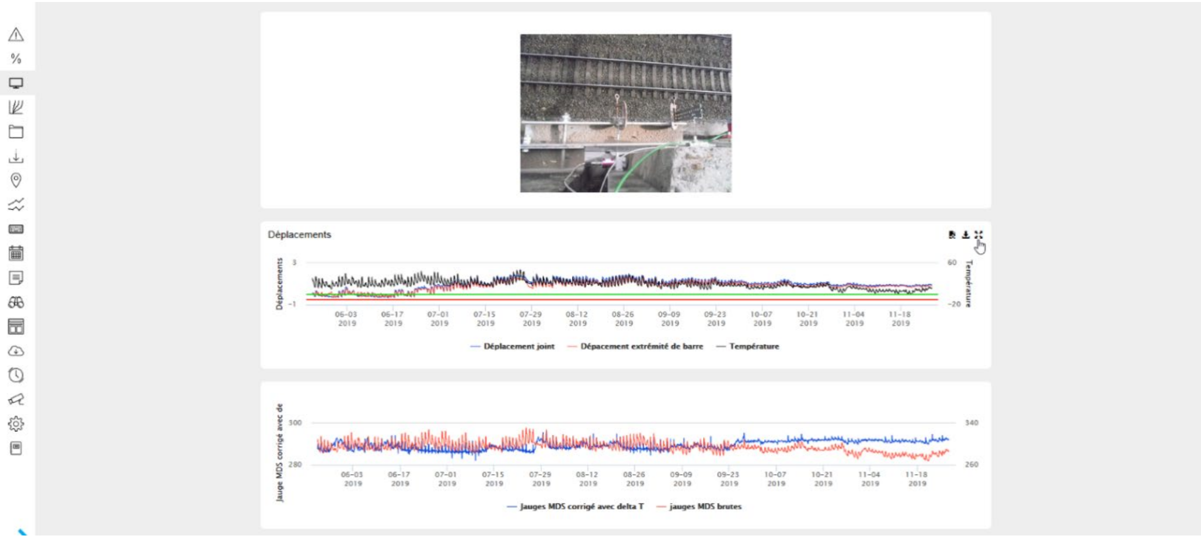

Figure 16 Web data platform

Figure 17 Two alarms set based on the monitored data: (left) alarm on the strain of the rod and (right) alarm on the inclination of the wall.

3.3.3 Capabilities of BDOA within the INFRACOMS architecture model

An initial, basic assessment of BDOA in the context of the INFRACOMS generic data architecture model suggests that BDOA has the ability to meet several components of the model. It is able to ingest and store datasets, but there are limitations to the types of data it can ingest, such as the difficulty in integrating videos, 3D models and dynamic data. Wallonia NRAs can consider addressing this issue in future updates. The current system allows users to check data for each type of measurement but does not facilitate easy interaction among different types of measurements. For instance, it is not possible to directly link temperature data with deformation data, which could be a potential area for future development.

The capability of the Wallonia Bridge Management System (BDOA) and web data platform can be summarised as illustrated in Figure 18. From our assessment of the system, the functions not currently supported include ingesting unstructured data such as videos, data processing using machine learning methods. However, as noted above for iROADS, this is an initial assessment based on an overview of the system. The assessment does not provide an assessment of the level of complexity that may be experienced when trying to implement new data within the system - see Section 6.

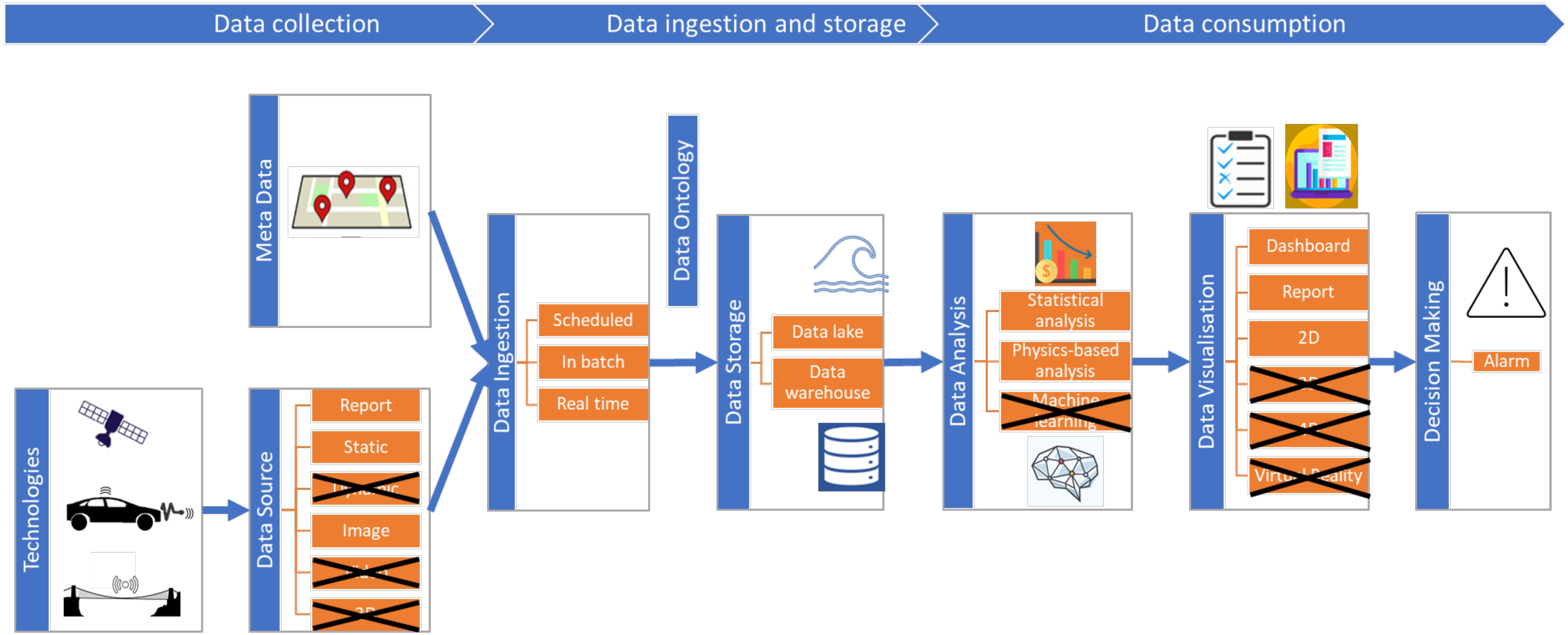

Figure 18 Reflection of the Wallonia bridge manage system to the INFRACOMS data architecture model. The functions not currently supported are stroked through, which are ingesting of dynamic data, video and 3D data, and data processing using photogrammetry and machine learning.

3.4 Summary observations on the reviewed existing data architectures

INFRACOMS has described a generic data architecture model, as described in Section 2 - Figure 3. Using this model as a reference, we have compared the abilities of two example data architectures to handle emerging technologies. For each segment of the pipeline in the generic data architecture model we have asked questions to better understand the existing data architecture, drawing on the structured approach shown in Appendix A.

The summary capability of the systems in relation to the architecture is outlined in Table 5. Our findings suggest that these current data architectures are capable of incorporating most types of data and of providing real-time or near real-time information for decision-making processes. As monitoring technologies, data analysis, and visualization methods evolve, architectures in NRAs may need to expand to include the following:

- Improved capability to process new types of data, such as dynamic, video, and 3D model data, to keep pace with the varied data types emerging technologies generate,
- Data processing via machine learning to benefit from the growing use of machine learning tools,
- Integrating advanced data visualization methods such as VR and 4D (which includes time as the 4th dimension), to accommodate new data visualisation methods.

Table 5 Capabilities of the two existing data architectures in relation to the INFRACOMS data architecture model

Segment in the INFRACOMS model	Questions		iROADS	BDOA+data web
Data collection	What type of data can the architecture ingest?	Report	Yes	Yes
		Static data	Yes	Yes
		Dynamic data	Yes	No
		Images	Yes	Yes
		Videos	Yes	No
		3D models	Yes	No
Data ingestion and storage	In what frequency can the architecture ingest data?	In batch	Yes	Yes
		At scheduled timing	Yes	Yes
		At any real time	Yes	Yes
	What is the level of automation?	Automatically through API	Yes	Yes
		Manually	Yes	Yes
	How does the architecture categorize the data?	According to metadata	Yes	Yes
		According to data type	Yes	Yes
		According to the measured performance indicator	Yes	Yes
Data consumption	What kind of data analysis can the architecture offer?	Machine learning	No	No
		Physics-based analysis	Yes	Yes
		Statistical analysis	Yes	Yes
	What kind of data representation can the architecture offer?	2D plot	Yes	Yes
		3D plot	Yes	No
		4D representation	No	No
		VR	No	No
		Real-time alert for decision making	Yes	Yes
		Producing report	Yes	Yes
		Dashboard	Yes	Yes
	What levels of decision making can the architecture offer?		Network Scheme operational	Global structural Local structural Non-structural

4. A system to appraise the ability to integrate data into an existing data architecture, and to support decisions

4.1 Appraising the ability to integrate data from new technology into an existing data architecture

In the above sections we have presented a data architecture pipeline (Figure 3) and undertaken an outline assessment of the components of two existing data management systems in the context of this data architecture pipeline (Table 5). However, whilst this is an informative breakdown of the key data architecture components of these systems, this analysis does not enable an NRA to understand, or appraise, the challenges that may be encountered if they wanted to introduce new types of data into those systems, and to store, analyse and visualise this new data. The key to appraising the ability to integrate new technology into an existing data architecture lies in how well the technology aligns with the capability of that existing data architecture. Therefore, the appraisal calls for information from both the technology and the data architecture.

In this section, we present an approach that could be applied to appraise the ability to integrate a proposed new data type into an existing data architecture. The appraisal is based on scoring the anticipated complexity of implementing the new data within each part of the data architecture pipeline. It is based around a scoring sheet (shown in Table 6) which covers the following aspects:

- Data collection, including Data source type and Data fidelity
- Data ingestion and storage, including Data ingestion frequency, Data ingestion automation, and Data organization.

Note: the other part of data architecture – data consumption – is not covered within this section. The consumption regarding data analysis and visualisation has previously been presented and appraised in report D3.1. The consumption regarding decision making is discussed and appraised in section 4.2.

The scoring sheet in Table 6 presents a summary description of the basis for awarding each score within each element. Further information on the distinction between scores is provided in the paragraphs following the table.

In section 5 we present an example of the application of the appraisal approach to assess the ability to integrate data from Acoustic Emission into the existing data architecture of Wallonia.

Table 6 Appraising the ability to integrate new data into an existing data architecture – scoring sheet

Final Score	Data source type	Data fidelity	Data ingestion frequency	Data ingestion automation	Data organization
5 – Data integration is easy, direct, reliable and automatic.	The pre-defined data format can be directly integrated into the data architecture.	The complete data are reliable.	The data acquisition frequency meets the data ingestion frequency of a data architecture.	The data are automatically integrated into the data architecture, for example through API. Software is available.	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.
4 – Data integration needs some help from experts, but generally is easy and reliable.	The data need to be exported to a certain format to be integrated. The data exportation is easy.	The useful part of data is reliable.	The data acquisition frequency is higher than the data ingestion frequency. Data can be stored and batched. Complete data are available.	Automated data integration is possible. Internal experts can easily develop the interface.	The data are sufficiently organized for the specific need. For other implementation, more organization is needed.
3 –Data integration needs experts and is sufficiently easy and reliable.	The data need to be exported to a certain format to be integrated. The data exportation needs experts.	The data can be validated easily.	The data acquisition frequency is higher than the data ingestion frequency. Data are too large to be stored and batched. Only scheduled data can be used. The data not on schedule will be lost.	Automated data integration is possible. External experts are needed to develop the interface.	The data are not organized, but have metadata containing enough information for organizing.
2 – Data integration needs experts heavily and can be reliable.	The data need to be processed and only the results in a certain format can be integrated. The data processing is easy.	The data can be validated by experts.	The data acquisition frequency is lower than the required data ingestion frequency, but sufficient.	Automated data integration is hard. Data need to be transmitted manually.	The data are not organized, and the metadata is not ready but achievable.
1 – Data integration needs experts heavily and requires more cost and labour to achieve reliable integration.	The data need to be processed an only the results in a certain format can be integrated. The data processing needs experts.	The data are hard to be validated.	The data acquisition frequency is lower than the required data ingestion frequency. Critical information is missing.	Automated data integration is hard. Data need to be transmitted manually by experts.	The data are not organized, and the metadata is not easily achieved.

4.1.1 The data source type

To appraise the data source type, it is important to determine if the data type produced by a technology aligns with the data types the current data architecture can manage. Therefore, this appraisal is not concerned with how advanced a technology is; instead, it focuses on how well the data type matches the data architecture's capabilities. For instance, a technology that merely generates reports may score higher than a technology that produces 3D models if it's intended for integration into a data architecture that cannot handle 3D models.

- The top score 5 signifies that raw data can be directly integrated without any processing, illustrating the highest compatibility between the data source type and the architecture capacity.
- Scores of 4 or 3 indicate that raw data cannot be directly ingested but can be exported to a compatible format for the data architecture. For example, if a data architecture only supports Excel files, strain measurement data must be converted into Excel format. The raw data file format could vary, depending on the data acquisition system. The distinction between scores 4 and 3 depends on the ease of data exportation.
- Scores of 2 or 1 denote that raw data requires processing before it can be integrated into a data architecture. For instance, if a data architecture can't handle dynamic data, acoustic emission signals need processing and analysis, and only the results in a static format (e.g., parameters, plots, or reports) can be ingested. The difference between scores 2 and 1 is determined by the ease of data processing.

4.1.2 The data fidelity

Data fidelity refers to the extent to which data is accurately and reliably represented. High-fidelity data is data that is highly accurate and precisely reflects the real-world phenomenon or system that it represents. Data, to be ingested into a data architecture, should meet a certain requirement of data fidelity.

- Scores 5 and 4 are awarded when data is trustworthy. Complete data reliability is given a higher score as it not only serves present needs but also future ones.
- When data reliability is uncertain (Scores 3, 2 and 1), validation becomes crucial. The scores are adjusted based on the effort needed to validate the fidelity of the data to be integrated into the architecture.

4.1.3 The data ingestion frequency

Evaluating data ingestion frequency primarily focuses on whether the data acquisition rate aligns with a data architecture's ingestion frequency. For instance, some architectures may not support real-time data ingestion, allowing only batch data ingestion at specific intervals or missing some data.

The advancement of a technology with a high data acquisition frequency doesn't guarantee a higher score if the architecture can't accommodate such frequencies. Excessive data can overload the architecture or necessitate substantial processing.

- The top score 5 is awarded when the technology's data acquisition frequency perfectly matches the ingestion frequency the architecture can handle.
- Scores 4 and 3 are for conditions when data is acquired more frequently than an architecture can ingest. If data can be stored and batched for later ingestion, a higher score is awarded. A lower score is assigned if data cannot be stored, and only data available at the ingestion time can be used.

- Scores 2 and 1 apply when the data acquisition frequency is lower than the architecture's data ingestion frequency. This actually leads to a reduced data ingestion frequency. A higher score is given when the reduced data ingestion frequency is still adequate for decision making, while a lower score is assigned when the frequency is insufficient, causing crucial data loss.

4.1.4 The data ingestion

The evaluation of data ingestion automation level mainly concerns the ease of ingestion.

- The top three scores reflect the feasibility of automated data ingestion, with distinctions made based on the ease of achieving automation.
- Scores 2 and 1 reflect situations where data must be uploaded manually, with a lower score assigned when even expert intervention is required for data transmission.

4.1.5 The data organization

Data organization primarily relates to the level of organization applied to the data ingested into the architecture, ensuring it's ready for subsequent analysis.

- The top two scores 5 and 4 apply when the data is organized. The specific score given depends on the level of organization that meets the needs.
- The remaining lower scores relate to conditions when the data is not organized but can be organized depending on the availability of metadata. Score 3 applies when metadata is available for data organization, Score 2 applies when metadata isn't readily available but can be obtained, and Score 1 applies in the worst case where metadata cannot be easily achieved, essentially indicating that the data cannot be organized.

4.2 Appraising the potential to support practical decision-making

Before assessing the potential of technologies to aid in decision-making, NRAs need to specify the type of decisions they intend to make. As addressed in Section 2.4, decisions can vary in scope, ranging from the network level, scheme level, and operational level for road asset management, to the global structural level, local structural level, and non-structural level for bridge asset management.

Different levels of decision-making have distinct requirements on the data provided by technology. For instance, a long-term decision like setting a national speed limit at the network level may require data updated on a monthly basis. However, if the decision is related to daily operations, such as traffic management in response to accidents, then data with a higher frequency, potentially updated hourly, would be necessary. Consequently, the evaluation of a technology's potential for aiding decision-making is heavily influenced by the specific use case.

The appraisal approach is based on scoring the anticipated factors that contribute to effective decision-making (Table 7). Each column in Table 7 presents a specific critical aspect. The table allows stakeholders to objectively compare technologies and their support for decision-making. This approach promotes transparency, adaptability, and efficient asset management decisions.

Note: while the appraisal factors may share some similarities with those discussed in the previous evaluations of data analysis, visualization, and integration into data architecture, such as data quality and frequency, these elements are specifically evaluated within the context of decision-making in this section.

The scoring sheet in Table 7 presents a summary description of the basis for awarding each score within each element. Further information on the distinction between scores is provided in the paragraphs following the table.

An example in which we appraise the potential for acoustic emission data to support decision-making is given in Section 5.

Table 7 Appraising the ability of the new data/technology to support decision-making

Final score	**Is data quality sufficient for decision-making?**	**Is data acquisition frequency sufficient for decision-making?**	**Can (processed) measurements be directly used in decision making process?**	**Advantages / Disadvantages**
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.

4.2.1 Is data quality sufficient for decision-making?

This criterion assesses the quality of the data collected through the technology. It evaluates whether the data is accurate, reliable, complete, and relevant enough to support informed decision-making. High-quality data ensures that decisions are based on reliable information and reduces the risk of errors or misleading conclusions. In this regard, for evaluating data quality sufficient for decision-making, the following aspects could be considered.

- Accuracy: The data should be accurate and precise enough to support reliable and confident decision-making about asset maintenance, repair, or replacement. Inaccurate data can lead to incorrect decisions and unnecessary expenditures.
- Completeness: The data should be complete, covering all the relevant aspects of asset condition that are important for decision-making. Missing data can lead to incomplete or biased assessments, which can also result in incorrect decisions.
- Consistency: The data should be consistent over time and across different data collection methods, allowing for reliable comparisons and tracking of changes in asset condition. Inconsistent data can lead to misinterpretation and confusion in decision-making.
- Relevance: The data collected should be relevant to the specific needs and goals of the asset management program. This means that the data should be targeted to specific decision-making needs, such as predicting pavement performance or identifying maintenance needs.

4.2.2 Is data acquisition frequency sufficient for decision-making?

This criterion focuses on the frequency at which data is acquired by the technology. Timeliness of data is crucial for effective decision-making, especially in asset management where conditions can change rapidly. Sufficient data acquisition frequency enables stakeholders to have up-to-date information, allowing them to make timely decisions and respond promptly to any issues or changes in asset conditions. The technology used for asset condition monitoring should capture the relevant features of the asset condition with sufficient frequency and precision for the required decision. This ensures that the data accurately represents the asset's condition and provides valuable insights for decision making. Real-time monitoring and data acquisition systems can help ensure that the data is available promptly to support decision making.

Some decision types may not necessitate real-time data. For instance, establishing network-level national speed limits doesn't require immediate updates, and a data frequency of months might be sufficient. Thus, the sufficiency of data frequency for decision-making is dependent on the specific use case.

4.2.3 Can (processed) measurement be directly used in the decision making process?

This criterion evaluates whether the measurements provided by the technology, after being processed or analysed, can be directly utilized in the decision making process. It examines whether the technology offers actionable insights or recommendations that can be readily applied to asset management decisions. Technologies that provide processed measurements in a format suitable for decision-making streamline the process and enhance efficiency.

For instance, consider a road condition monitoring technology that utilizes various sensors to collect data on pavement condition, such as surface roughness, cracking, and distress. After processing and analysing this data, the technology generates a comprehensive report that includes an assessment of the pavement's current condition, a prediction of its future deterioration, and recommended maintenance actions. In this case, the criterion of whether the measurements provided by the technology can be directly utilized in the decision-making process focuses on the ability of the technology to offer actionable insights. The technology should provide specific and quantifiable data on the road's condition, allowing asset managers to make informed decisions regarding maintenance and repairs. For example, if the technology identifies a high-risk section of road that requires immediate attention due to severe cracking and a declining ride quality, it enables the asset manager to prioritize resources and allocate funds accordingly.

By delivering processed measurements in a format suitable for decision-making, the technology facilitates streamlined and efficient decision-making processes. The actionable insights and recommendations provided by the technology enable asset managers to proactively plan and implement maintenance strategies, maximizing the lifespan and performance of road infrastructure while optimizing resource allocation.

4.2.4 Advantages/Disadvantages

This criterion delves into the inherent strengths and weaknesses of the technology concerning its contribution to the practical decision-making process. It entails a thorough assessment of how the technology enhances or hampers decision-making effectiveness. Evaluating these factors helps stakeholders understand the overall benefits and drawbacks of incorporating a particular technology in the decision-making process, ensuring alignment with the specific requirements of asset management objectives. For instance, a technology that offers real-time data visualization and user-friendly interfaces could expedite decision-making processes by providing actionable insights, while a technology with limited data compatibility might hinder seamless integration with existing asset management systems, posing operational challenges.

5. Example technology and use case – acoustic monitoring for post-tensioned steel wire rupture detection of bridge cables

This section demonstrates the application of the appraisal process (i.e. appraising the ability to integrate new technology into an existing data architecture and to support decision-making) to the example use case of acoustic monitoring for the detection of post-tensioned steel wire ruptures in bridge cables. This provides continuity with D3.1 in which we applied the appraisal process for data analysis and data visualization to the same technology (Section 4.6 of report D3.1).

5.1 Data architecture

To appraise **integration into the data architecture**, we consider the Wallonia bridge management system - BDOA and the web data system, as our reference architecture, given that our selected use case focuses on bridge monitoring. We have appraised the compatibility of this acoustic data with the Wallonia bridge management system based on the aspects described is Section 4.1 (Table 6) above.

Data source type

Given the capabilities of the Wallonia data architecture as reviewed in Section 3.3, we understand that it can manage static data, reports, and images, but it falls short in accommodating dynamic data, videos, and 3D models. The raw Acoustic Emission (AE) signals are dynamic, possessing a high sampling rate, which cannot be directly ingested into this architecture. The most feasible alternative is to export certain parameters into easily digestible formats like Excel, text files, figures or reports. These parameters could include the number of hits, signal strength/energy, frequency components, estimated event location, etc. The process of exporting these post-processed parameters is straightforward, and there's even an option to utilize commercially available software to aid in this task.

- Based on these considerations, a score of 4 is assigned for the data source type, corresponding to '<u>4 - The data need to be exported to a certain format to be integrated. The data exportation is easy</u>.'

Data fidelity

Acoustic data is susceptible to interference from environmental noise, particularly when dealing with data that has a lower signal-to-noise ratio. A straightforward solution involves applying a threshold to filter out noise, thus ensuring the remaining data is considered reliable.

- As such, we assign a data fidelity score of '<u>4 - The useful part of data is reliable</u>.'

Data ingestion frequency

The web data platform within Wallonia's data architecture scans for new data every 5 minutes, yet acoustic data can have a sampling rate as high as 1M per second. It's clear that the data acquisition frequency greatly exceeds the data ingestion frequency accommodated by Wallonia's data architecture. However, data collected in between scans can be batched and ingested later. .

- Consequently, we assign a data ingestion frequency score of '<u>4 - The data acquisition frequency is higher than the data ingestion frequency. Data can be stored and batched. Complete data are available.</u>'

Data ingestion automation

In the Wallonia system, sensor data is uploaded in real-time to an FTP server. Although there is no established experience in uploading AE data, we anticipate that, with assistance from external experts, an interface for uploading AE data to the FTP server could be created.

- Therefore, we assign a data ingestion automation score of '3 - The automated data integration is possible. External experts are needed to develop the interface.'

Data organization
With respect to data organization, acoustic emission (AE) data is well-structured, with metadata explicitly included. However, given the complexity of data interpretation, experts may need to reorganize the data for different implementations.

- As such, we assign a data organization score of '4 - The data are sufficiently organized for the specific need. For other implementation, more organization is needed.'

Considering the above aspects, a final score of '4 - Data integration needs some help from experts, but generally is easy and reliable' is given to integrating AE data into the Wallonia bridge management system. Table 8 shows the scoring result regarding to integration AE data into Wallonia bridge management system.

Table 8 Example of scoring the integrating acoustic emission data into Wallonia data architecture.

Final Score	Data source type	Data fidelity	Data ingestion frequency	Data ingestion automation	Data organization
5 – Data integration is easy, direct, reliable and automatic.	The pre-defined data format can be directly integrated into the data architecture.	The complete data are reliable.	The data acquisition frequency meets the data ingestion frequency of a data architecture.	The data are automatically integrated into the data architecture, for example through API. A software is available.	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.
4 – Data integration needs some help from experts, but generally is easy and reliable.	The data need to be exported to a certain format to be integrated. The data exportation is easy.	The useful part of data is reliable.	The data acquisition frequency is higher than the data ingestion frequency. Data can be stored and batched. Complete data are available.	The automated data integration is possible. Internal experts can easily develop the interface.	The data are sufficiently organized for the specific need. For other implementation, more organization is needed.
3 –Data integration needs experts and is sufficiently easy and reliable.	The data need to be exported to a certain format to be integrated. The data exportation needs experts.	The data can be validated easily.	The data acquisition frequency is higher than the data ingestion 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.	The data are not organized, but have metadata containing enough information for organizing.
2 – Data integration needs experts heavily and can be reliable.	The data need to be processed and only the results in a certain format can be integrated. The data processing is easy.	The data can be validated by the experts.	The data acquisition frequency is lower than the required data ingestion frequency, but sufficient.	The automated data integration is hard. Data need to be transmitted manually.	The data are not organized, and the metadata is not ready but achievable.
1 – Data integration needs experts heavily and requires more cost and labour to achieve reliable integration.	The data need to be processed an only the results in a certain format can be integrated. The data processing needs experts.	The data are hard to be validated.	The data acquisition frequency is lower than the required data ingestion frequency. Critical information is missing.	The automated data integration is hard. Data need to be transmitted manually by experts.	The data are not organized, and the metadata is not easily achieved.

5.2 Decision-making

Appraising the potential to facilitate decision making is performed according to the criteria described in Section 4.2 - Table 7. It should be noted that the scoring depends on the specific use case necessitating decision-making. In this evaluation, we assess the potential of AE to aid decision-making in relation to wire ruptures in external post-tensioned steel cables in a concrete bridge girder.

Is data quality sufficient for decision-making?
As noted earlier, the reliability of AE data can be enhanced through certain data processing methods (besides proper on-site calibration), such as employing a threshold to mitigate environmental noise. Therefore, instead of simply stating that the data is sufficient, we consider that its quality can be significantly improved.

- This evaluation includes the frequency of data collection, leading to a score of '4 - Yes, the quality of the data can be made sufficiently high, considering also the frequency with which the data are collected'.

Is data acquisition frequency sufficient for decision-making?
The frequency of AE data is exceptionally high, reaching approximately 1 million readings per second. This frequency is considerably more than sufficient for practical decision-making.

- Thus, we assign a score of '5 - Yes, the data acquisition frequency is sufficient for decision making, given the quality of the data'.

Can (processed) measurement be directly used in the decision-making process?
In relation to the use case - identifying wire ruptures using AE data - the processed details such as the number of AE hits and signal strength can be used to indicate a wire rupture. We consider that the processed data can facilitate decision-making related to wire rupture.

- As a result, we assign a score of '4 - Yes, after some processing, the data can easily be used in the decision making process'.

Advantage/Disadvantage
For the specific use case of wire rupture detection, besides on-site calibration, minor modifications such as establishing an appropriate threshold to filter noise are required, as mentioned previously.

- Thus, we assign a score of '4 - The technology needs some minor adaptations in order to make it fully operational for practical decision-making'. However, it's important to note that this might not apply universally. Under certain circumstances, data from other sources may be required to support decision-making. For instance, in the scenario of long-term monitoring of wire breakages, environmental data (e.g., rainfall) would be needed to assess their impact. In such a case of long-term monitoring, the score would be '3 - Advantage: the technology provides additional, useful information; Disadvantage: other data must also be available'.

Considering the above aspects, a final score of '4 - Useful data for practical decision making but some adaptation is needed' is given to the potential of AE to support decision making related to wire rupture in steel cables. **Error! Not a valid bookmark self-reference.** shows the scoring result of the example.

Table 9 Example of scoring the potential of acoustic emission for supporting decision making related to wire rupture in steel cables.

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.

6. The overall appraisal process

6.1 The four aspects of the appraisal process

This report, along with report D3.1, develops a system to appraise technologies across four critical aspects: data analysis, data visualization, integration into existing data architecture, and the potential for practical decision-making. Report D3.1 elaborates on the first two dimensions (data analysis and visualization), while this report, D3.2, covers the latter two (data integration and decision making).

This system serves as an advanced and more comprehensive evaluation tool following the initial pre-evaluation provided in the appraisal toolkit. It is our expectation that the NRAs will gain a deeper understanding of how a specific technology aligns with their decision-making needs.

6.2 Visualisation of the outcomes

The appraisal process provides a set of scores across a range of criteria. There is benefit in visualising these scores to obtain an "overview" of the appraisal. We suggest that the results be presented in the form of a radar diagram, to provide NRAs with a comprehensive and easily digestible visualization, while also giving them the flexibility to prioritize the aspects that are most relevant to their needs. Figure 19 presents the radar diagram illustrating the evaluation results for our chosen example and use case: Acoustic Emission Monitoring of Wire Rupture in external post-tensioned Bridge Cables. Regarding the evaluation of integration into existing data architectures, Wallonia bridge management system is chosen. This example spans across the two reports under discussion.

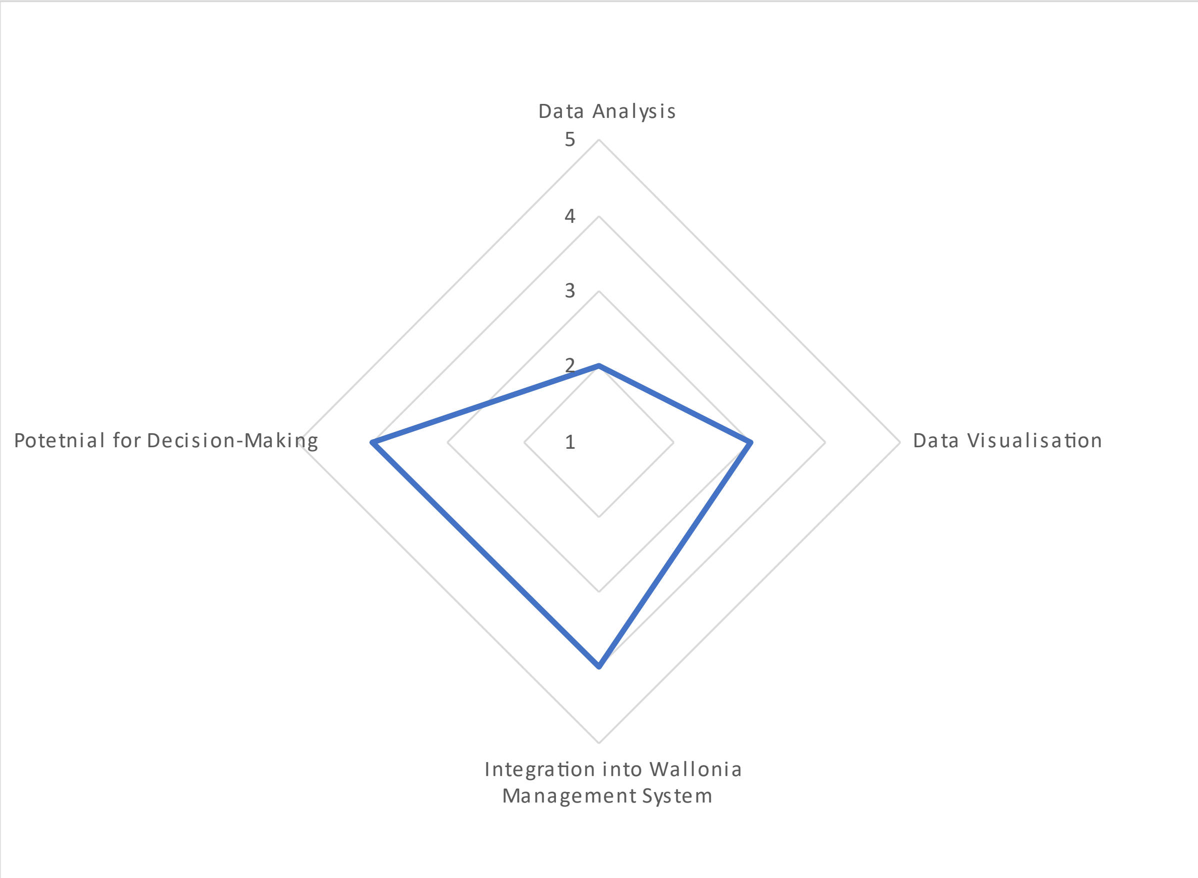

Figure 19 presentation of the appraisal results as a radar diagram for the example case – acoustic emission monitornig of wire rupture in external post-tensioned bridge cables.

6.3 Further examples

The scoring results of the other 20 technologies in Database 1.0 with technology readiness level over 7 are listed in Table 10.

A broad review of the scores indicates that technologies with lower Technology Readiness Levels (TRLs), such as wireless acoustic emission, may receive lower scores in data analysis and visualization. This makes sense as technologies with lower TRL are often new, and their data analysis and visualization may necessitate expert input, resulting in generally lower scores according to our evaluation system.

It's important to acknowledge that scoring cannot be completely objective. It hinges on the evaluator's comprehension of the technologies, their identification of decision-making, and their understanding of the data architecture. The same technology evaluated by different individuals could yield different scores. A solution could be peer scoring.

Table 10 The scoring of technologies in Database 1.0 with technology readiness level over 7.

ID	Appraisal carried out by	Appraisal Score				Technology name	TRL
		Data Analysis	Data Visualis-ation	Decision – making	Data architech-ture		
1	COWI	4	4	5	4	Crowdsourcing vehicle telemetry (Friction)	9
3	COWI	4	4	4	5	COWI virtual inspection platform	9
4	COWI	4	4	5	4	EpsilonRebar	9
6	COWI	1	2	5	4	Acoustic emission	7
7	TU Delft	2	3	4	4	Wireless Acoustic emission	7
8	TRL	4	4	to be specified	3	Crowdsourcing vehicle flow data	9
9	TRL	4	4	4	3	Crowdsourcing comfort data	8
13	TRL	4	3	4	to be specified	Aerial/satellite Spectroscopy - Using Cband technology to monitor fixed points for movement	8
15	TRL	4	3	5	to be specified	Automated detection and classification of highway assets (in particular, signs)	8
20	DTI	4	4	5	5	EyeVi Platform - point cloud generation	8
21	ZAG	5	2	5	3	VMX - 2HA (lidar mapping system) + Road Data Information System (RoDIS)	8
28	TRL	4	5	5	to be specified	Air Quality Monitoring System AirSensor	7

29	BRRC	3	3	3	3	Crowdsourcing road noise data	8
38a	TRL	3	3	4	3	Weigh-In-Motion - Bridges [For use for single Bridge Monitoring]	9
38b	TRL	4	3	4	3	Weigh-In-Motion - Bridges. Road sensors being repurposed for use in network Bridge Monitoring.	9
40	TU Delft	3	5	4	4	Optical fibres	9
53	BRRC	3	3	4	4	LIDAR	9
55	BRRC	5	5	5	4	Instrumentation of a cycle path (InfraLytics)	7
57	BRRC	2	3	3	4	Multi-Speed Deflectometer (MSD)	9
59	ZAG	4	4	4	4	Traffic safety and infrastructure evaluation based on artificial intelligence	9

6.4 Investigating the appraisal process in greater depth, and refinement to guidance

As discussed in previous sections, the application of the proposed architecture appraisal process draws on the completion of the questions posed in Appendix A, ideally supported by a discussion with relevant experts (users/builders of the target system). This should provide a strong foundation to understand the ability / complexities of implementing new data within a specific target system (to meet a specific use case). However, this appraisal provides a mainly "theoretical" assessment. This desk-based appraisal scoring may not provide a complete understanding of the level of complexity that might be experienced when physically trying to implement the new data within the system. It is likely that a more complete appraisal would require practical/more detailed investigation of the actions required at each stage of the process in the context of the specific technology and the proposed use case. For example, this may require access to example data and working this though the appraisal process to understand the level of practical complexity in loading, storing, processing and visualising that specific data.

The application of the appraisal process in greater depth will be the subject of the case studies that will be explored in Work Package 4 of INFRACOMS. The lessons learnt and outcomes of the case studies will be used to refine the process where appropriate, and to support the development of further guidance on the application of the process within the INFRACOMS Appraisal toolkit.

Appendix A. Questions to understand existing data architecture

To effectively assess the integration of a new technology into an existing data architecture, several questions related to data architecture practices need to be addressed. These questions are raised according to the described segments in the generic data architecture in Section 2. (Multiple selections are allowed.)

- What type of data source can the data architecture handle?

  ☐ report

  ☐ static data, e.g. strain measurement

  ☐ dynamic data, e.g. acoustic signals

  ☐ images

  ☐ videos

  ☐ 3D models

  ☐ others:

- In what frequency can the architecture ingest data?

  ☐ in batch, i.e. complete data can be integrated into the data architecture in batch.

  ☐at scheduled timing, i.e. only data at certain timing can be integrated into the data architecture.

  ☐ in real time, i.e. complete data can be integrated into the data architecture at any in real time.

  ☐ others:

- What is the level of automation for data ingestion?

  ☐ automatically through API

  ☐ manually uploaded

  ☐ others:

- How does the data architecture categorize and organize the data (data ontology)?

  ☐ according to the metadata (e.g. time and location of the measurement).

  ☐ according to the type of data source (static, dynamic, images,…)

  ☐ according to the measurement parameter (displacement, crack, friction,…)

  ☐ no data organization can be performed by the data architecture (unstructured data).

  ☐ others:

- What kinds of data analysis capabilities does the data architecture offer?

☐ Artificial intelligence-based analysis

☐ Physics model-based analysis

☐ Statistical analysis

☐ others:

- What kinds of data representation capabilities does the data architecture offer?

☐ 2D plot, e.g. line plot, heat maps, tree maps, Sankey diagrams etc.

☐ 3D plot, e.g. integrating into a BIM model

☐ 4D representation, including time-series data

☐ Virtual Reality and Simulation

☐ Dashboard

☐ Producing report

☐ others:

- What levels of decision making does data architecture offer?

(for road management system)

☐ Network level: decisions which affect the entire network, such as deciding maintenance budgets and national speed limits

☐ Scheme level: decisions regarding planned maintenance and construction

☐ Operation level: day-to-day decision making, such as traffic management, responding to incidents and asset failure

☐ others:

(for bridge management system)

☐ Global structural level: decisions which affect the global safety of the bridge, preventing bridge collapsing

☐ Local structural level: decisions which affect the serviceability of the bridge components but will not influence the entire bridge

☐ Non-structural level: decisions which affect the utility of non-structural elements of the bridges like railing, drainage system, lights and etc.

☐ others:

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