Towards European standardization of digitalization approaches for monitoring and safety of bridges and tunnels

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ABSTRACT: This paper reports about preparatory work for future standardization that is carried out through an EU coordination and support action titled IM-SAFE. It focuses on applied digital technologies for monitoring and safety, including predictive maintenance of bridges and tunnels. Amidst the improved affordability of digitalization technologies and techniques, the biggest challenge in monitoring and maintenance of bridges and tunnels is no longer about collecting data as much as possible, but about obtaining and exploiting meaningful data throughout the lifecycle of the built assets. An effective and efficient data-driven approach is important to allow both human experts and computers to make accurate diagnostics, predictions, and decisions. Further standardization is seen as an important part to reach that goal.

The work in IM-SAFE related to ICT standardization focuses on the following topics: (1) the general requirements and pre-conditions for high-quality and cost-effective acquisition, transmission, storage and processing of monitoring datasets to ensure the data is fully accessible and machine-interpretable; (2) the relations between the future standards in structural engineering with the open ICT standards for interoperability, especially on Internet of Things (IoT), Building Information Model (BIM), Geographical Information System (GIS), and Semantic Linked Data (LD); (3) a common design of IT platforms to manage monitoring and asset management data of transport infrastructures; (4) the ways to facilitate data analytics technologies, including AI, to be applied for monitoring and asset management of transport infrastructures, and to assess the added value of data-driven approach next to physics-based modelling.

With regard to these topics, this paper reports the outcomes from the expert and stakeholder consultations that recently took place within the IM-SAFE pan-European Community of Practice.

1 INTRODUCTION

1.1 *Objective*

The EU coordination and support action titled IM-SAFE is paving the road towards ensuring the safety of the European transport infrastructures. The main goal of this project is to support the preparation of a mandate to the European Committee for Standardization (CEN) for improving and renewing the European standards for monitoring, safety and maintenance of transport infrastructures.

Digitalization plays a key role in the future standards. Many technological innovations have been developed and there is a growing number of best practices with digital solutions for transport infrastructures. This paper addresses standardization of digitalization approaches for monitoring and safety of bridges and tunnels, with the focus on data acquisition and quality assurance, data interoperability, cloud platforms for monitoring data, big data analytics, and the use of artificial intelligence.

1.2 *Outreach to practice*

In order to crystallize the importance of digitalization in the future CEN standards for transport infrastructures, to share the best practices among the industrial players and government bodies, and to collect feedback on the proposed standardization approach, the IM-SAFE project organized a pan-European meeting with the Community of Practice (CoP) on 24 February 2022. This paper reports the substance and the discussions in the symposium.

1.3 *Structure of this paper*

In the following section, a brief state-of-the-art review on digitalization for transport infrastructures is provided. Subsequently, this paper presents a summary of the symposium sessions on 1) Smart sensing and imaging; 2) Artificial Intelligence; 3) Data interoperability; 4) Remarks from European Commission officers. Finally, brief concluding remarks are presented.

2 DATA REVIEW OF INTEROPERABILITY IN MONITORING AND MAINTENANCE

Data interoperability is among the main challenges in the construction industry where different domains and stakeholders need to share information about the building or asset. “Data silos”, each owned and managed by different stakeholders, are a huge barrier for efficient collaboration. This situation calls for the development of open standards covering different use cases in design, construction, and asset management.

For monitoring and predictive maintenance, which is the scope of this paper, it is not necessary to develop completely new ICT standards. Instead of new standards, existing open standards in Internet of Things (IoT), Building Information Modelling (BIM) and Geo Information Systems (GIS) can to be combined to benefit from the available technologies. Since these standards have become quite complex, further agreements on how to use them for particular use cases are needed. Such agreements are important (1) to capture data exchange processes as well as (2) to define how to manage different data sources from semantic and technical point of view. This chapter provides a brief overview of the results of the IM-SAFE project regarding data interoperability in monitoring and maintenance of transport infrastructures.

2.1 *Generic workflow of data lifecycle*

Monitoring comprises collecting and processing data about the physical building. Like design and construction processes, it can be a highly diverse process with different types of measurements and subsequent data filtering, normalizing and evaluation steps. The generic workflow is described in the next section and it could be applied as a guideline for on-site inspection and monitoring using integrated IoT and digital twin concepts.

Each of the described steps deals either with the generation or the processing of data. Aside from data acquisition, each process step receives input from the results of the preceding steps in the workflow. Since each step relies on different technologies, various data formats are used for transmission and processing. Therefore, each step needs a different standardization approach to ensure interoperability throughout the entire workflow.

1. The first step is the generation of data using digital measuring devices. The types of these devices can vary. Data acquisition can, for example, be done using stationary sensors embedded in the structure, unmanned aerial vehicles (UAVs), or manually operated measuring devices. The gathered data and their format depend on the type of device and manufacturer. Here, standardization regards the procedures to use data acquisition devices/output data to/from the devices.
2. The second step is the data transmission from the on-site devices/systems to the cloud storages. Standardization in the areas IoT, open APIs, measures for data security and quality is needed to ensure connectivity between all relevant actors of the process.
3. The third step is the creation and management of information models. For further use, the unstructured data from the measuring devices need to be transformed into an information model. Depending on the application, several information models need to be created and aggregated. Standardization takes place in the areas of data structure/decomposition and Level of Details (LoD) for open BIM and GIS.
4. Next, the data collected in the process usually needs to be processed to serve as a foundation for decision supports. Data from BIM or GIS models can be used as input for a Finite Element Model (FEM) and the designated software computational tools. The relevant standardization for this step of the workflow regards the conversion from information models, such as BIM, to FEM. The goal of this standardization is to minimize manual effort for BIM-to-FEM.
5. Finally, for data-driven decision-making, it is necessary to present the collected and produced data in a clear way. Depending on the tools used throughout the process, different visualization techniques are used to present data in different ways. Non coherence in data representations can lead to biased decision-making . Therefore, standardization is needed with regard to the level of information shown depending on the use case. Different disciplines (e.g., architecture, MEP engineering, etc.) could profit from standardized Model View Definitions (MVDs) to present the relevant information in a structured way.

2.2 *Open standards for data interoperability*

The generic workflow as discussed in the previous chapter shows different types of data being generated, processed and shared. Three main areas related to data interoperability can be identified, namely IoT, BIM and GIS. The various standards and proposals that have been developed by different standardization bodies as well as enterprises are partially overlapping in terms of scope (see Figure 1). Between BIM and GIS, the overlap positively supports in the ability for georeferencing of the built assets without having to cover the whole infrastructure networks. The overlap between BIM and IoT open standards regards the physical representations of the sensor hardware, including its basic properties. This overlap positively enables locating where measurements are done without having to store the measurement data directly.

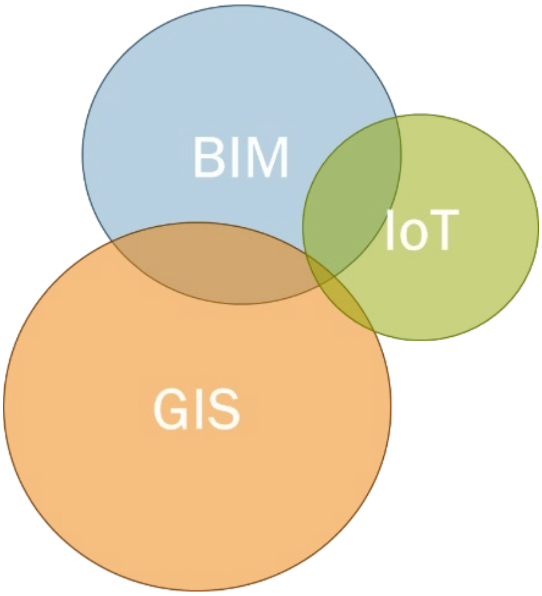

Figure 1: Main areas with overlapping scope

While no existing standard can cover all data exchange requirements, defining a new standard from scratch is not preferred by the industry. Accordingly, the preferred direction is looking into existing open and proprietary standards and enable them to understand how they can be reused for monitoring and maintenance of transport infrastructures.

In the IoT area, open standards for data transmission have been established, making it possible to use devices from different manufacturers in a common system. To integrate sensor data from IoT systems, it is necessary to assign a position to the sensors in the BIM model. For the purpose of integrating IoT data into BIM models, there are both proprietary and open-source solutions. Among the open-source approaches to integrate IoT data in BIM models, there are different ontologies that aim to provide a common information model for sensors and actuators of different manufacturers, such as SAREF SSN/SOSA and Brick. These ontologies can be used to combine topological data from an IFC (Industry Foundation Classes) BIM model with the information models for building elements (i.e. Building Element Ontology), and/or product properties (i.e. PROPS Ontology).

The scope of BIM is quite extensive as it is supposed to be a digital representation of a built asset covering its whole life cycle, i.e. from first conception, design, construction, asset management till refurbishment or dismantling. The term “BIM” basically describes a new way of working, which is also implemented in information standards and software. Today, beside national or use case specific standards, the main international BIM open standard is IFC (ISO 16739), which is developed by the non-profit organization buildingSMART.

This open standard provides core functionalities for describing the physical representations of a built asset, including the basic properties, element connections, breakdown structures, element aggregations and the functional grouping into systems. The IFC schema goes beyond a reference structure and enables, for instance, describing construction processes and resources, and idealization of load-bearing structures and model constraints. The latest version of IFC includes support for bridges and the next version is expected to cover tunnels as well.

Along with BIM, the GIS data serves as a structured and interoperable basis in the life cycle of a built asset. GIS supports the planning, the integration into the environment and the visualization of construction projects. With the help of GIS data, BIM can be extended to include a geographical context, such as surrounding environments, protection zones and 3D city models. Standardization in the field of GIS in particular is already well advanced, largely due to the INSPIRE Directives by the European Commission. In the transport infrastructure sector, GIS data is usually taken as the basis for planning, as it describes the current situation. In order to bring the GIS and BIM worlds together, it is firstly necessary to distinguish whether an information model involves transformation/conversion or linking of information. The different approaches each have advantages and disadvantages.

In the GIS domain, CityGML open standard is commonly known. When transforming IFC BIM models into CityGML GIS models, existing limitations are recognized. Not all concepts of the IFC data schema can be fully mapped; this can result in a loss of information. In addition, complex geometries cannot always be mapped with a sufficient accuracy. Constructive elements are often missing during the transformation of CityGML and geometries cannot always be described unambiguously due to different description methods. To solve this, linking of models at the application, process, or data level is recommended so. no information will be lost since all models exist separately in their respective formats.This approach assumes the existence of appropriate software solutions that perform the linking and represent the linked data models, which is explained further in the following section in this chapter.

2.3 *Data management with Linked Data*

Looking into monitoring and maintenance of transport infrastructures, it becomes clear that different stakeholders and tools are involved and that all need to work together. However, they also have different views on the built assets to be monitored and maintained. It is commonly recognized that there is no single standard covering all aspects related to the lifecycle of a built asset and its environment. Consequently, established standards coming from different domains, being maintained by different standardization bodies, and additionally being based on different technologies, must work together in a heterogeneous and distributed environment. Well-known ICT organizations, namely IEEE, ISOC, W3C, IETF and IAB, have published the "OpenStand Principles" (https://open-stand.org/) addressing topics related to standardization and its joined use.

The challenge of bringing all these developments together is tackled by various projects relying on Linked Data principles, mostly using Semantic Web technology for its implementation. However, it does not mean that all data must be accessible as web-enabled content. The focus is rather on shared data and all resources that need to be referenced by other data domains. For that purpose, the Semantic Modelling and Linking standard has been developed to provide guidelines about how to use the semantic web technology to harmonize and integrate different data sources (prEN 17632:2022).

Implementations and technical solutions are currently pushed by the (Semantic) Digital Twin concept, which in fact is about having a holistic, up-to-date digital representation of a built asset. Monitoring and predictive maintenance use cases can naturally benefit from Digital Twin developments.

3 REPORT OF THE PAN-EUROPEAN MEETING WITH THE COMMUNITY OF PRACTICE

An activity of the IM-SAFE EU Coordination and Support Action is organizing pan-European Community of Practice (CoP) in support of the renewing the standards for monitoring, maintenance and safety of transport infrastructures. On 24 February 2022, a CoP symposium was dedicated to the topic of digitalization. This symposium consisted of three technical sessions and a concluding session by the representatives from the European Commission.

3.1 *Smart sensing and imaging*

The first symposium session was dedicated to best practices and challenges regarding digital data acquisition. In this session, best practices examples from INSITU - Spain, were presented, followed by a technical presentation by SACERTIS – Italy. Subsequently, a panel discussion was conducted involving experts from HOCHTIEF ViCon – Germany, FERROVIAL – Spain, The Norwegian Public Road Authority, and TNO – The Netherlands.

The best practice examples from INSITU showed the three-dimensional (3D) laser scanning and software processing for roads, and laser scan installations for railways. The examples included real implementations and outcomes from several infrastructure projects.

In the technical presentation by an expert of SACERTIS, the roles of digitalization in handling the infrastructure management process were described from tripolar points of view, namely: functionalities, users and data. The expert further explained the implementation of digitalization in the structural health monitoring (SHM) knowledge field and the utilization of a customized digital platform for structural engineers in collaboration between SACERTIS and IBM.

In the panel discussion, several important topics related to digital data acquisition were highlighted. An expert of HOCHTIEF ViCon addressed data integration concept from three viewpoints: stakeholders, IT systems for construction, and project data. An expert from FERROVIAL underlined the main challenges for digitalization in infrastructures in relation with the needs for validated technologies before implementation, access to innovation funding, and digital capabilities of construction workers. An expert of the Norwegian Public Road Authority shared the operation of the control and monitoring centers for bridges and tunnels in Norway. An expert from TNO pointed out to the diversity between different European countries in the use of standards and digital solutions for structural monitoring.

3.2 *Artificial Intelligence*

The second symposium session was dedicated to best practices and challenges regarding the applications of Artificial Intelligence (AI) in transport infrastructures. In this session, best practices examples and a technical presentation from IBM Research – Switzerland were given. Subsequently, a panel discussion was conducted involving experts from KNOWCE – Italy, IBM Research, and Rijkswaterstaat an agency of the Ministry of Infrastructure and the Environment, The Netherlands.

The best practice examples and technical presentation by IBM Research addressed the use of AI for visual inspection of civil infrastructures. Several examples of the combined use of AI and robots/drones for inspection were shown. Furthermore, an example was provided about a scalable, cloud-based platform the 'One Click Learning IBM Research Platform' and its functionalities.

In the panel discussion, several important topics related to applied AI were highlighted. An expert of KNOWCE discussed about leveraging AI technologies to support civil engineers with defect recognition and diagnostics for extending the life of the structures through predictive maintenance. An expert of IBM discussed the use of drone technologies along with automated smart imaging analysis that bring new dimensions and higher value for civil infrastructure asset management. An expert of Rijkswaterstaat shared the collaboration between public clients, researchers and students to create innovative yet practical solutions on AI.

3.3 *Data interoperability*

The third symposium session was dedicated to best practices and challenges regarding data interoperability in transport infrastructures. In this session, best practices examples and a technical presentation from TNO – The Netherlands and AEC3 – Germany were given. Subsequently, a panel discussion was conducted involving experts from TNO, TU Dresden – Germany, Deutsche Bahn – Germany, and NEN – The Netherlands.

The best practice example showed by TNO and AEC3 was about the project INTERLINK funded by the Conference of European Directors of Roads (CEDR) that delivered a standardized roadmap for ‘asset information management using Linked Data for the lifecycle of roads’. The result comprised data modelling and linking principles for exchanging and sharing information about roads among the stakeholders within and across European countries.

The technical presentation by an expert of AEC3 highlighted the data interoperability challenges along the “3M” of information Model (data and semantics), information Modelling (processes, workflows and information flows), and information Management (data access and technologies). The presentation also emphasized the existing standardization on data interoperability in various domains, such as in BIM (e.g. IFC), in GIS (e.g. CityGML), in Linked Data (e.g. Road-OTL by CEDR, EU INSPIRE Directive), in IoT (e.g. SAREF, Brick). A short overview about these topics is provided in chapter 2.

In the panel discussions that followed, several important topics related to data interoperability were highlighted. An expert of TU Dresden reflected on 30 years of research in data interoperability and the ongoing challenges with regard to making full-automatic data interoperability based on standardized computer-interpretable languages. An expert from Deutsche Bahn summarized the main barriers to the interoperability of railway data, i.e. risks/breaches in the digital support of processes and workflows with internal and external partners; incoherent IT applications, tools and proprietary exchange formats; inconsistent data availability, poor integration and linkability of the existing data. An expert of TNO underlined the importance of FAIR data principle (Findable, Accessible, Interoperable, Reusable), and the enabling of FAIR data via W3C Linked Data & Semantic Web Technology. Finally, an expert from the Dutch standardization committee, NEN, described the structures for international standardization and reminded the IM-SAFE consortium of benefitting from the existing EU and international standards in the ICT domains. The relevant standards for digital data interoperability include:

- CEN/TC 442 - Building Information Modelling
- ISO/TC 184 - Automation systems and integration
- SC 4 Industrial data
- SC 5 Interoperability, integration, and architectures for enterprise systems and automation applications
- ISO/TC 59/SC 13 - Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)
- ISO/TC 10 Technical product documentation
- ISO/TC 46 Information and documentation

3.4 *Remarks from European Commission officers*

In the final session of the symposium, two European Commission officers shared their views.

Rafal Stanecki from DG MOVE shared the information about the European Strategy for Data with the main goal of building a common European data space: a single market for data. On digitalization of transport infrastructure, he emphasized the provisions for smart and resilient transport on the EU TEN-T corridors, including:

- Article 42: ICT systems for transport, in particular: other dimensions of data sharing covered, including optimisation of supply chains, Internet of Things (IoT) devices, etc
- Article 44: new technologies and innovation, in particular: new element of cyber security
- Article 45: safe and secure infrastructure, in particular: firm requirement to ensure that transport infrastructure provides for safe and secure passenger and freight movements
- Article 48: resilience of infrastructure, with the objective to maintain the infrastructure in a way that it provides the same level of service and safety during its lifetime
- Article 48: maintenance and project life cycle

Konstantinos Gkoumas from the Joint Research Centre summarized the expectations and challenges for the digitalization of transport infrastructure with regards to:

- new and emerging digital technologies can revolutionize the way structures and transport infrastructures are designed, build and maintained, such as: digital twins, UAVs, IoT, AI, machine learning, vision-based monitoring, indirect monitoring, etc.;
- needs for interdisciplinary teams, breaking the silos, linkages/transition between different disciplines;
- paramount importance of standardization, data interoperability and security;

- roles of digitalization to enable the sustainability transition; and
- technologies that are supported by policy and implementation actions at several levels.

4 CONCLUDING REMARKS

Digitalization is an enabling technology for modern monitoring and predictive maintenance approaches for transport infrastructures. The overview provided in this paper related to ongoing efforts in the digitalization area shows the existence of well-defined monitoring and maintenance processes supported by developments in open standards for data. The implementation of open data standards depends on the monitoring and maintenance use cases, also in consideration of the being long-term processes involving many different systems, technologies and stakeholders. Standardization needs to take into account the existence of diverse ICT environments at the stakeholders' organizations.

The available software solutions and open data standards provide a good basis for implementation of monitoring and predictive maintenance use cases. A number of major technical challenges have been addressed by various standards in BIM, GIS and IoT, and the knowledge can be reused and adopted to the asset management of transport infrastructures. Generic methodologies, for instance Information Delivery Manuals and Semantic Modelling and Linking guidelines, as well as best practice examples from research and industry show how to get started with the necessary specifications and implementation of open standards. Reusing this knowledge and experience, as presented in the IM-SAFE CoP Digitalization Symposium, will help to solve a lot of typical ICT-related challenges, and enable benefitting from the ongoing open standard developments efficiently.

Looking ahead, it is important to understand the principles of semantic data integration in order to be able to step-by-step enlarge the scope and support new use cases in monitoring and maintenance of transport infrastructures, which will arise with new measurement equipment and data processing solutions like Artificial Intelligence (AI), Machine Learning (ML), etc. Applying the semantic web technology is a continuous effort that should be done based on regular reviews of existing and emerging solutions. Having this in mind, it is important to get started with the ICT-based data processing and data interoperability solutions. Using linked data and semantic web technology will ensure the necessary flexibility to follow such a gradual approach. Relying on this principle and the data workflow presented in this paper will facilitate data sharing that is properly documented in open ways.

One of the main challenges for the research community is to contribute to such standardization efforts by finding the right balance between technology being ready for standardization and new innovative approaches that will use and extend the standards in the future.

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