ACTUAL AND FUTURE CONTEXT OF TRANSPORT INFRASTRUCTURE MONITORING AND MAINTENANCE

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Lead Author	Sara Cuerva Navas (FER)
Other Authors	Jochen Köhler (NTNU), Frida Liljefors (NTNU), Lisa Ptacek (BOKU), Jos Wessels (CROW), Paola Darò (SAC), Matthias Weise (AEC), Florian Fliegel (AEC), Juliusz Zach (MOSTOSTAL), Alfred Strauss (BOKU), Inge Hoff (NTNU), Isabella Alovisi (SAC), Linda Abspoel-Bukman (TNO)
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Preface

This strategic report aims to provide an overview on current and future trends, needs, standardised methodologies, challenges and main research lines related to monitoring and maintenance of transport infrastructure. The report includes the Executive summary (Chapter 1) and Infographics (Annex 1) for dissemination at political and public administration level.

Chapter 2 explains the IM-SAFE project context and includes a brief explanation of the needs for research and standardization in Europe, together with a description of the methods and the approach pursued in this report.

The In chapter 3 the current status in structural maintenance, safety assessment and monitoring is analysed. Here basis is taken in an intensive dialogue with relevant stakeholders on regional and on Pan-European level. While the detailed report on this dialogues is documented in Appendix A1 and A2, chapter 3 contains the corresponding catalysation and summary of current state of practice, research and development and standardisation. The chapter is concluded with the identification of the stakeholder perspective on the major trends for future developments.

In chapter 4 the accumulated state of current knowledge relevant to structural maintenance, safety assessment and monitoring is aggregated to a concise description of a rational procedure and the main challenges for practical implementation are highlighted.

How current best practices can transition towards more rational risk oriented approaches, how this can be supported by standards and how these standards can be developed is discussion in chapter 5, that also contains direct implications for the further work and developments of the IM-Safe project.

The document concludes with an extensive final section comprising the applicability of the current practices in infrastructure monitoring and maintenance, a summary of the outlook, providing proposals for future actions, and furthermore, complementary insights from best practices across Europe, risk analysis on barriers and lessons learned.

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1 Executive summary

Bridges and tunnels are the critical nodes on the transport infrastructure networks which are vital for the functioning and growth of European and regional economy. The transport systems empower the free movement of passengers, goods and services, enabling the creation of economic wealth. Guaranteeing infrastructure's safety is key for the built environment and the continuity of Europe's progress and lifestyle. In the recent years, safety risks have become critical and manifested in major disasters, that in many cases were a consequence of structural failures due to maintenance deficiencies. Infrastructure's safety can't be compromised and its proactive maintenance is of utmost importance. However, the actual resources and capacity for inspection and conservation of infrastructure are very limited and need an extra support to counteract the growing backlog of maintenance. This support can be provided by technology. Over the last years, there have been unprecedented technology advances that can enable the change towards new monitoring and maintenance techniques and strategies. Standardisation is the key to ensure that those techniques and strategies are implemented in an optimised and transparent way that meets the actual needs of the European infrastructure.

The Trans-European Transport Network, the TEN-T, has more than 1234 km of bridges with more than 100 m span and 775 km of tunnels and their malfunctioning could cause enormous impacts. Most of the current infrastructures across Europe were built between 1960 and 1970 and were designed for a 40 to 50 years lifetime. However, their aging has been accelerated in the recent years. Two of the main aging triggers are the increase in traffic loads and flows, together with the changes of environmental exposure for which bridges and tunnels were not designed. The forecast is that mobility needs will continue to grow and that the intensity and frequency of the natural hazards to which the infrastructures are exposed will continue increasing. Therefore, quick and efficient action needs to be undertaken, since the actual regulations are lacking to consider the impacts of these events in infrastructure preservation.

Accurate information from monitoring of structures is crucial to take the right decisions on maintenance and safety: optimal maintenance is only possible with the right policies and decisions enabled by timely and accurate information. The transition from the current practice, based on corrective and time-based maintenance approaches, towards a data-informed, condition-based and risk-based approach leads not only to higher reliability and availability of the infrastructure but also to a more cost-optimal asset management. Given the central role of information in the future practices, monitoring is perceived a key enabler for ensuring the safety of the infrastructure. Many best practices are already in use in Europe and a lot of research projects are working on increasing the TRL of their technological solutions. However, the existing knowledge and experience with monitoring is not consistently interpreted and implemented in different European countries. Standardization of principles, methods and procedures is the key to facilitate the envisaged transition.

Due to the fact that infrastructure is aging, immediate actions are required. Technology is mature enough, there is a lot of know-how across Europe and there is the common will to reach consensus among the involved stakeholders to improve the current practice. IM-SAFE project aims to support the European Commission and the European Committee for Standardization (CEN) in preparing new standards in monitoring for optimal maintenance and safety of transport infrastructure based on a comprehensive insight into trends & challenges, PEST barriers, best practices, and technology & knowledge developments. This strategic report has the purpose to provide an overview on current and future trends, needs, standardised methodologies, challenges and main research lines related to monitoring and maintenance of transport infrastructure. This overview is the starting point for the mandate for CEN.

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Based on an intensive dialog with relevant stakeholders consisting of infrastructure owners, consulting engineers and authorities from across Europe the need for modern standards for maintenance, safety assessment and monitoring/inspection became evident. Infrastructure owners confirm the increasing pressure from aging bridge and tunnel infrastructure with increasing numbers of structures that call for careful reconsideration of structural safety and efficient planning of mitigation measures. The sheer number of objects that infrastructure owners have to deal with require effective and systematic strategies that have to be supported by standards. The analysed applied practice for maintenance, safety assessment and monitoring/inspection is characterized by a large variability among countries. Furthermore, most applied strategies might be attributed as “hazard prevention”, i.e. they might in most cases sufficient to provide safety, but they fail in providing a strategy for the optimal long-term provision of safety.

Thus, standardisation is found to be required for harmonisation of practices across Europe. It is considered as a key factor for enabling transition from corrective maintenance towards cost-optimal predictive risk-based and data-informed maintenance of infrastructure. In the dialogue, stakeholders confirm that the current state of standardisation does not support them in the relevant assessments and analysis that is required for condition control, safety evaluation and maintenance planning. Necessary assumptions and modelling choices are taken often by individual consultants with the corresponding implications on responsibility and liability. This does not promote the application of modern advanced methods and leads often to a conservative judgement with negative implication on efficiency. The performed analysis of the existing know-how, has confirmed that a consistent methodological framework for rational decision making for structural maintenance, safety assessment and monitoring can be established. The alignment to the currently applied practices reveals the main challenge that have to be addressed by the future standards and the corresponding development. Outcomes of the IM-SAFE project reported in this deliverable set the path of transition for the most critical aspects.

The already proven best practices, the ongoing local developments and the state-of-art concepts should be accommodated for in future standardisation, keeping in mind that the following two general needs for future standardisation shall be acknowledged: the future standards shall be open enough to ensure the integration of present developments towards risk-based management of infrastructure, and shall enable the application of advanced methods and provide for an uptake of recent and future research findings to the benefit of present and future structural maintenance, safety assessment and monitoring. The path “from the needs to standardisation” has been clearly set.

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2 From needs to standardisation

2.1 Safety of Ageing Infrastructure

In the light of the tremendous societal challenges associated with the necessary green shift towards a more sustainable development the traffic infrastructure is an important element as it binds a huge amount of financial and environmental resources and at the same time it is crucial for the safe and efficient exchange of goods and services. In Europe, transport systems empower the free movement of passengers, goods and services, enabling the generation of economic wealth and the import and export of goods and services to and from other regions beyond Europe (Group, 2017). Europe's transport systems are highly dependent on the road and railway infrastructure networks, which carry more than 80% of passenger and 50% of goods transport (MOVE, 2019). The Trans-European Transport Network, the TEN-T, has more than 1234 km of bridges with more than 100 m span and 775 km of tunnels (bridges and tunnels are the main assets that IM-SAFE project is targeting) and their malfunctioning could cause enormous impacts (NETWORK, 2018).

Most of the current infrastructures across Europe were built between 1960 and 1970 and were designed for a 40 to 50 years lifetime. However, their aging has been accelerated. Two of the main aging triggers are the increase in traffic loads and flows, together with the weather condition changes for which bridges and tunnels were not designed (Pérez, 2019), (AXA, 2014). Back then, and even at the end of the 20th century, transport infrastructures were designed considering the criteria that met the back then required conditions and the prospect of future mobility estimated. However, the unprecedented technology advances have allowed much greater mobility than expected (OECD, 2012). Besides, in the last years, the frequency of extreme events related to meteorological phenomena has increased exponentially. Events such as heat and cold waves, floods, droughts, storms, or fires are now more recurring and present a great hazard for the stability of the infrastructures, as well as for the safety of their users (UIC, 2017). In fact, the second generation Structural Eurocodes have plans for addressing the changing climate (Denton, 2021), as for example, scaling factors as the basic wind velocity, temperature, etc. to calculate the reliability of structures ((Bigaj-van Vliet, Allaix, Köhler, & Scibilia, 2021), more importantly, in maintenance, inspection and monitoring of the existing ones.

In Europe, more than 50% of the bridges have reached the end of their designed service life and on top of that, as mentioned before, most of them carry significantly more traffic load than what they were originally designed for (Gkoumas K, 2019)). Besides, considering the latest technological advances (truck platooning, automated driving in convoy, smart routes, etc.), most probably, the traffic load on bridges will continue to increase in the coming years.

In the past, most of the resources were designated to bridge design and construction to overcome mobility and connectivity problems. However, now, the situation is different. In the developed countries, in and among Europe, there is a huge amount of existing bridges. Maintenance deficiency accelerates the structural deterioration and increases the risk for the safety of infrastructure (Casas, 2015). For example, across the United States there are more than 617,000 bridges. 42% of them are over 50 years old, and 7,5% are structurally deficient although 178 million trips are taken across them every day. (Card, 2019). In Europe, the European Construction Industry Federation (FIEC) estimates that 60% of the post-war structures have problems related to bars corrosion because of the ageing of the concrete structures. These problems are getting worse because of the cuts in public budgets and its subsequent maintenance scarcity and the loss of talent that is reportedly moving to the private sector (Commission, 2019). Since the 2008 global crisis, the EU has invested less in transport

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infrastructure and the infrastructure is degrading because of the insufficient maintenance budgets, which have been cut or not evolved according to the needs (Transport, 2019). After the collapse of the motorway bridge in Genoa, Italy, in 2018, the European countries seem to be more aware of the state of their infrastructures, as for instance back then the following was stated (Kim Illsher, 2018):

- In France, the government stated in a study that a third of its road bridges required repairs and that 841 posed a potential risk.
- In Italy, 300 bridges were at risk of failure.
- In Germany, a 2017 report written by the Federal Highway Research Institute found that only 12.4% of the road bridges were in bad condition, however a similar percentage was considered to be in good condition.
- In Bulgaria, the government was planning to renovate more than 200 bridges. Most of the targeted bridges were structurally deficient and are around 40 years old.

Recent tragic disasters of bridges and tunnels in Europe such as the ones stated below, caused by a combination of structural, natural and human factors, highlight the need for coordinated actions:

- Hintze Ribeiro Bridge, in Entre-os-Rios, Castelo de Paiva, Portugal. The pillar foundation became compromised due to years of sand extraction and the central span collapsed in 2001. 59 people killed.
- Bridge on SS9 over River Po in Piacenza, Italy. It collapsed due to flood of River Po in 2009. 1 person injured.
- Several bridges in Cumbria, England. Very intense rainfall produced extreme river loads that overwhelmed all the bridges in 2009. 1 person killed.
- Myllysilta bridge in Turku, Finland. The bridge bent 143 centimetres due to structural failures of both piers in 2010.
- Skjeggestad Bridge, in Holmestrand, Vestfold, Norway. Partial pier displacement due to a landslide in 2015.
- Himera Viaduct, in Scillato, Sicily, Italy. Partial pier displacement due to a landslide.
- Provincial road Ksanthi-Iasmos at Kompsatos river crossing in Eastern Macedonia and Thrace district, Greece. The cause of its collapse in 2017 is under investigation.
- Troja footbridge, in Prague, Czech Republic. Probably corrosion or damage of the suspension cables, 4 people injured.
- Polcevera viaduct, in Genoa, Italy. It collapsed in 2018. 43 people killed.
- Pont de Mirepoix, in Mirepoix-sur-Tarn, France. It collapsed due to overweight traffic in 2019. 2 people killed and 5 injured.
- Viadotto Madonna del Monte on A6 Highway (Savona-Torino), in Savona, Italy. It collapsed in 2019 because of heavy rain and landslides.

Beside bridges, similar concerns affect tunnel and other types of infrastructure as there have been major tunnel disasters in Europe; the most notorious examples are: Kaprun (Austria, 2000, 155 casualties), Mount Blanc (France-Italy, 1999, 39 casualties), Tauern (Austria, 1999, 12 casualties), Gotthard (Switzerland, 2001, 11 casualties), and Frejus (Italy, 2005, 2 casualties).

2.2 Pathways of future-oriented standardisation

Accurate information from monitoring of structures is crucial to take optimal decisions on maintenance and safety; unfortunately, there are gaps in the existing European standards and the monitoring practice at national level.

Structural monitoring is not adequately addressed in the current Eurocodes (CEN/TC 250), and the existing standards on monitoring are not consistently interpreted and implemented in

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different European countries due to a lack of coherent policies and the gaps in knowhow. The current standards do not embed the full extent of knowledge on:

1) performance analysis of diverse structural systems;
2) impacts of changing transport loads, natural and man-made hazards;
3) analytics of extensive measurement and monitoring data to provide input for optimal maintenance strategies and safe operation of the infrastructure; and
4) the adoption of digital technologies beyond the conventional inspection methods. The high diversity of transport infrastructure assets and their environments add to the complexity for standardised monitoring.

Development and adoption of new European standards involve complex processes that require multi-level dialogues, consensus and commitment from political and industrial stakeholders to move forward from legacy procedures.

The need for robust standardisation is generally acknowledged by public authorities and industrial stakeholders. However, developing new European standards based on national state-of-the-art is challenging as there are only a few existing national standards in this field with shortcomings in their coverage and technical depth. Getting a broad acceptance for the new standards will also be difficult, especially if changes in the existing procedures and agreements on monitoring and maintenance are implied. Standardisation thus requires dialogues and discussions about responsibilities, liabilities and accountabilities among the policy-makers, public clients, design and engineering consultants, and construction firms – the key stakeholders in the currently fragmented value-chain in construction.

For optimal safety, availability and cost-effectiveness of transport infrastructure, future-oriented standards <u>require to promote a paradigm shift</u> from the time-based/corrective maintenance <u>towards risk-based/predictive maintenance through data-informed decision-making. This is enabled by a harmonised set of procedures for monitoring, including a standardised digitalisation approach.</u> The new standards should be supported and implemented coherently by the public authorities and the industrial stakeholders across Europe.

The societal-need for safe and resource efficient infrastructure requires that <u>risk-based maintenance strategies will be embedded in infrastructure management systems</u> to ensure safety over the infrastructure assets' lifetime. Assessment of the structural condition will be based on the integration of inspections, monitoring and testing. The main advantage of such integrated approach is: the information gathered from the structures enables <u>timely and cost-effective decision-making</u> on repairs, strengthening and renovations. The gathered data will be used for <u>assessing the actual safety and the risk levels of the structure as well as for predicting the future safety and risks</u>. This is currently possible by using the latest digital innovations that integrate structural models, predictive degradation models and data analytics techniques. <u>The combined human expert and artificial intelligence</u> will result in the <u>transformation of measured data into knowledge</u> about the performance and safety of the structure. This will provide input for predictive maintenance, which in turn will guarantee the achievement of the required safety levels and will support the planning of an optimal maintenance for the assets.

<u>What crucially needed in the short term is: to stimulate and facilitate the transition</u> from traditional maintenance approaches (corrective and time-based maintenance) towards the risk-based approach by <u>standardising and harmonising the condition-based maintenance strategies and practices</u> at local, national and EU level. In this context, the advantages of performance monitoring will be fully exploited and compared to the conventional approaches based on visual inspections and non-destructive testing (NDT).

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New future-oriented standards for monitoring, safety assessment and maintenance of the structures should include the following essential aspects:

- Guidance about the physical parameters to be monitored and the performance / predictive analysis
- Guidance on how the monitoring data can feed the safety assessment and maintenance approaches
- Requirements on the algorithms used for damage identification
- Requirements on reliability, robustness, installation, operation, maintenance of sensors/monitoring systems

These aspects are still not covered within the ongoing mandate 515/m ("Mandate for amending existing Eurocodes and extending the scope of Structural Eurocodes") where CEN TC/250 is developing general procedures to use of structure-specific information in the safety assessment of existing structures.

2.3 Objectives of the deliverable and methodologies and approaches followed

The objective of this document is to provide a thematic inventory about the technical status and future pathway of maintenance, safety assessment and monitoring of civil engineering works in the traffic infrastructure (e.g. bridges, tunnels). This with special emphasis on the future social needs for sustainable development and the required advance of best practices and corresponding standards. This requires insight and overview in current best practices applied across Europe and the corresponding state of standardisation, as well as awareness about the future pathways and potential that is suggested by recent research developments in the field.

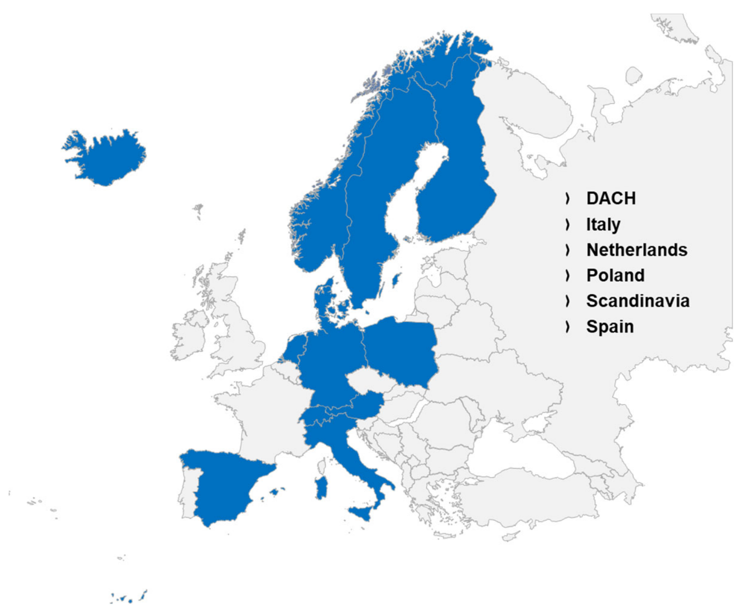

Figure 2.1 - Overview of the national CoPs

One main source of information used comes from workshops, interviews and questionnaires with IM-SAFE Communities of Practice (CoP). IM-SAFE consortium has created several CoPs in which representatives of national and regional authorities, public and private infrastructure asset owners and operators, construction and maintenance companies, design and

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engineering specialists, and, monitoring and ICT providers are involved. To date, 1 Pan-European meeting and 12 regional workshops with the CoP have taken place between 2019 and 2021, organised by countries:

1. DACH (Germany, Austria, Switzerland)
2. Italy
3. Netherlands
4. Poland
5. Scandinavia (Iceland, Norway, Sweden, Finland and Denmark)
6. Spain

In these workshops, representatives from 12 countries (see Figure 2.1), and more than 150 attendees that belong to 76 different entities (public entities, government agencies, infrastructure owners, engineering companies, consulting companies, construction companies, construction software developers, technology providers, research centres, universities, etc.) participated The main aspects discussed were around standardisation, the current practices, the needs and the challenges that the CoPs are facing in terms of monitoring, assessment and maintenance of bridges and tunnels. The outcomes of those workshops are included in this report.

Besides these workshops, IM-SAFE country representatives have contacted some of the stakeholders individually, to gain more knowledge on specific aspects that had not been covered in detail during the workshops, such as standards in use, details about monitoring platforms or asset management platforms, etc. Furthermore, an online form has been shared with all the CoP members to understand the use of specific technologies in each of the geographies and be able to picture the applicability of the most used monitoring and maintenance practices across Europe.

The second source of information comes from the available literature. More than 40 reports from DG GROW, DG MOVE, JRC, REFINET, PIARC, SAMCO, have been analysed by all consortium partners in detail, together with more than 50 applicable standards (national, regional, European, USA, etc.) such as: ISO 13822:2010, ISO 13824:2020, ISO 14963:2003, ISO 16857:2004 Italian UNI/TR 11634:2016, Norwegian SVV v411, DUTCH CROW-CUR 117, etc. Furthermore, more than 30 research papers have been analysed to have an idea of the past findings that could currently be applicable trends and information from the PatSat database from the ESPACENET has been used, in order to identify the most relevant patents in terms of bridge or tunnel maintenance around the world. A detailed list of these sources of information is included in Annex 4 of the present document.

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3 Current status in monitoring, assessment and maintenance of transport infrastructure

In the Annex 1 a detailed overview of the regional/national current practice and ongoing development is provided for various countries in Europe. Not only the countries in which IM-SAFE project has a Community of Practice have been analysed (DACH, Italy, Netherlands, Poland, Scandinavia and Spain), but also other European countries like Portugal, Latvia, Estonia, Lithuania, Czech Republic, Slovakia, Romania, Hungary, France, United Kingdom, and two countries outside Europe, the United States and China. In the following sections this information is presented in a synthetized way in order to provide an overview about the main aspects of the current status.

3.1 State of the Practice

This section covers what are the maintenance, assessment and monitoring practices in Europe, referring to the actual standards and general **current practices** already applied in the considered countries. This knowledge has been gained mainly thanks to the feedback provided by IM-SAFE Community of Practices (CoPs). Besides, the established standards and practices, new methodologies and techniques that are currently introduced for specific assets/areas are reported and discussed. These developments are not standardised, but they are already in use or are planned to be implemented.

Firstly, it is interesting to know that in the short term, bridge inspection will most probably look at the quantitative assessments of bridge performance and conditions rather than visual inspections and condition ratings (Hearn et al., 2000). Hence, the data would be collected by a variety of permanent sensors or any other technologies connected to wired or wireless networks (IoT). The deterioration shall be automatically detected by the data analysis and corrective actions will be planned.

The sensors are the key hotspots providing accurate and quantitative data, sensors that are getting more accessible and affordable because of the miniaturisation of hardware devices and the lower costs for communication. Some of the systems for measuring bridge performance may be:

- Embedded sensors for measurement of corrosion potential and current,
- Load cells permanently embedded into bridge bearings to allow periodic verification of load paths,
- Interferometry for surface flatness to detect aging in coatings and damage in fibre reinforced composite elements,
- Embedded fibre-optic sensors for crack detection and strain measurement,
- Permanent features in substructures for rapid mounting of laser systems for deflection measurements (permanent, dedicated mounting locations allow simple collection and comparison of response signatures),
- Vision-based systems,
- MEMS sensors such as clinometers and accelerometers for long-term static and dynamic monitoring, and
- Radar and infrared sensors housed in overhead bridge lighting and interrogated when weather conditions are favourable.

According to (Alokita Shukla, 2018) long-term structural health monitoring systems (SHM) have long been successfully employed in the monitoring of bridges. Among all the advantages of SHM systems, one major advantage is the monitoring of megastructures like bridges (Collins J, 2014). About 40 bridges with spans of 100 m or longer in the world were being

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evaluated with SHM systems already in 2004 (Ni YQ, 2004). Some of the most notable examples all over the world of enormous bridges monitored are the Great Belt Bridge in Denmark (Andersen EY, 1994), the Tsing Ma Bridge in Hong Kong (Lau CK, 2000), the Akashi Kaikyo Bridge in Japan (Sumitro S, 2001), the Commodore Barry Bridge in United States (Barrish RA, 2000), the Seohae Bridge in Korea (Kim S, 2002), and the Confederation Bridge in Canada (Cheung MS, 1997).

The application of long-term monitoring techniques have been implemented at the time of construction on some recently constructed bridges, such as the Shenzhen Western Corridor, the 4th Qianjiang Bridge, the Sutong Bridge (Hao Wang, 2016), and the Stonecutters Bridge (Wong KY, 2004). In the research of (Wong KY, 2004)there was major improvement in the monitoring system of the Stonecutters Bridge when compared to the Tsing Ma Bridge. The improvement includes the addition of advanced sensors such as corrosion sensors, hygrometers, barometers, and pluviometers (Collins J, 2014), as outlined in the introduction. There are some specific types of sensors like corrosion sensors, fibre-optic sensors, and strain gauge sensors that can be deployed only at the time of construction the bridge (Collins J, 2014). In recent years, the main focus of monitoring systems was on the monitoring of bridges' durability, integrity, and reliability. One of the best examples of this practice is the Sutong Bridge. The real-time data obtained by the embedded sensors are part of a stability and safety monitoring system composed by the following elements:

- Sensors subsystem,
- Data acquisition,
- Transmission subsystem, data management and control subsystem,
- Structural health evaluation subsystem

Nowadays, the need for a Bridge Management System (BMS), as IM-SAFE's Community of Practices confirm, is a known requirement to evaluate and maintain bridges. The bridge management systems have a specific method and a specific software for this purpose. As Mehran Ghomali (2013) mentioned "A bridge management system or BMS is a means for managing bridges throughout design, construction, operation and maintenance of the bridges." According to the Guideline for Bridge Management System (2004) "Bridge Management Systems help agencies to meet their objectives, such as building inventories and inspection databases, planning for maintenance, repair and rehabilitation interventions in a systematic way, optimizing the allocation of financial resources, and increasing the safety of bridge users". Besides, the same Guideline indicates that the desired output of a BMS should include a concise list prioritising the damaged bridges according to the urgency of the repair works and according to a so called condition ratio, together with the estimation of the cost of the repair works based on several maintenance strategies.

-DANBRO (Danish Bridges and Roads)	Denmark
-FinnRABMS (Finnish Naional Roads Administration Bridge Management System).	Finland
-DISK (Data Informatie Systeem Kunstwerken, Rijkswaterstaat) -CRIAM (Constructief Risico Indexering Afwegings Model, Rijkswaterstaat)	Netherland
-SAMOA (Surveillance, Auscultation and Maintenance of structures)	Italy
-MICHI (Ministry of Construction Highway Information Database)	Japan
-BMS.NRA (National Roads Authority) -SIHA	South Africa
-BSM (Lindblath, 1990)	Sweden

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-STEG (Structures Register) -HiSMIS (Highway Structures Management Information System) -BRIDGEMAN (BRIDGE Management system) -COSMOS (Computerized System for the Management of Structures)	England
-PONTIS (Preservation, Optimization and Network information System) -BRIDGIT (Bridge Information Technology) -PENBMS (Pennsylvania Bridge Management System)	USA

Table 3-1 - Bridge Management System (BMS) in developed countries ((Ryan T., 2012))

Below, more details of some of the different Bridge Management Systems used in some European countries are given:

- BaTMan (Bridge and Tunnel Management) is a web-based management system that has replaced a previous BMS named SAFEBRO. It is used for tunnels and bridges but also for other structures. Other asset managers, such as rail administrations, subway administrations, municipalities and so on, can use BaTMan. BaTMan uses other databases linked to other systems such as traffic database or a system for permissions for heavy vehicles.
- DANBRO (FHWA, 2005) is the Danish Bridge Management system. The system was first used in the 1980s, and in recent years, it has focused on storing all records, reports and data online, the data stored are inventory, engineering, drawing, reports and inspection data. The system identifies eight types of inspection. The inspector will recommend a repair scheme, its year of implementation, and an estimation of repair costs for each defect report.
- There is another system called DANBRO+ which offers maintenance management for special structures such as movable bridges, major crossing and tunnels. Lift mechanisms, traffic signals, navigation lights, ventilation, traffic control rooms, connected buildings, communications networks, surveillance cameras, and other sensors may be found in these structures. All of these require specialized knowledge to operate, evaluate, and maintain. Operating instructions, maintenance guidelines, and maintenance logs are all available through DANBRO+.
- The Bridge Management System in Finland started out as an inventory system. In the 1990s, new capabilities were added to analyze repair needs, prioritize projects, estimate budget needs, and forecast future trends. These roles have necessitated a change in data, particularly in the depiction of bridges as elements and quantities, as well as the relationship between condition data and maintenance and repair operations.

In general terms, each developed country has its own BMS that is being improved including new technologies (digitalization, IA, clouds, etc.) and new functionalities (decision-matrix, automatic budget calculation, etc.). In the following subsections, more detailed specifications for the BMS used in some countries can be found.

3.2 State of the current developments and R&D

A big effort at European (Gkoumas K, 2019) (Collins J, 2014) and international level has been made in the development of new research with regard to bridge maintenance and structural health monitoring. Specially, US and China, which are leaders in this fields, followed by other countries such as South Korea.

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These conclusions have been reached from the SCOPUS database (reference data base for scientific research). The following graph, in Figure 3.1, shows the evolution of peer reviewed scientific publications in the area of bridge maintenance and structural health monitoring in the last 20 years.

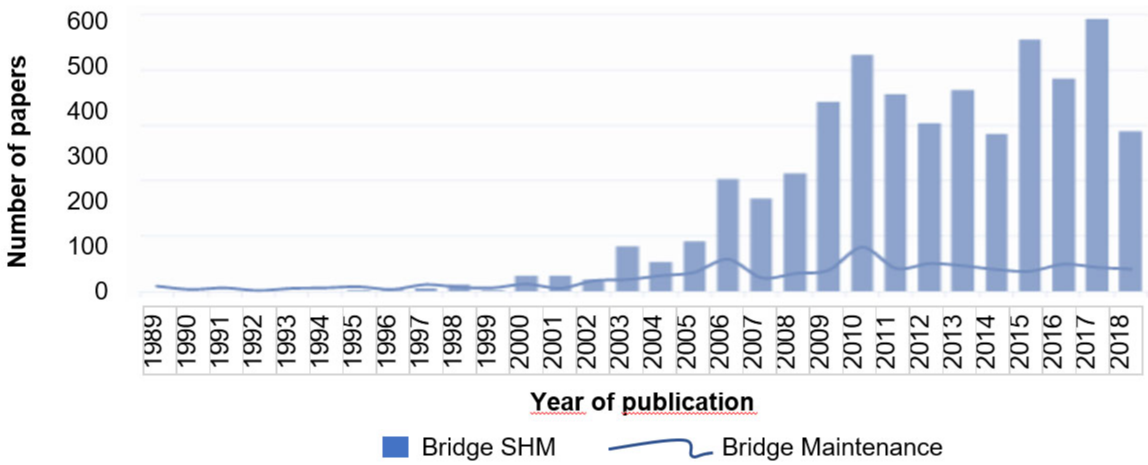

Figure 3.1 - Bridge research scientific papers (redrawn form source: Scopus, TRIMIS elaboration)

Since 2005, an almost linear increase can be observed, although in the last years it seems to have reached a stabilization.

Another source of information to analyse the trends in this field is the international IPR (Intellectual Property Rights) activity in the field of bridge sector, filtering by CPC (cooperative patent classification) code "G01M5/008" (although this search may be extended to other CPC). This area covers inventions on the elasticity of bridges. Using the PatSat database from the ESPACENET web portal in the period 2005-2017 the information obtained is the one shown in Figure 3.1, information that has been expanded in this document in Figure 3.3 in order to update the information provided in Gkoumas (2019) including 2021 provisory results. In short, by the analysis of both figures, it can be concluded that:

- There is a total of more than 300 patent fillings in the last 3 years. There is a peak in 2019 with around 200 patent fillings.
- China is the country that has filled the major number of patents, the majority of which have been filled in the last years. They cover almost 80% of the total number of fillings every year since 2015.
- US, Japan, Korea and Europe are also present in the landscape.
- The biggest increment in the last years can be a consequence of the developments in the new different technologies, such as drones.

Although, the search could be extended to other fields with different CPC codes, this first approximation could help to have a general overview of the main role players in this area.

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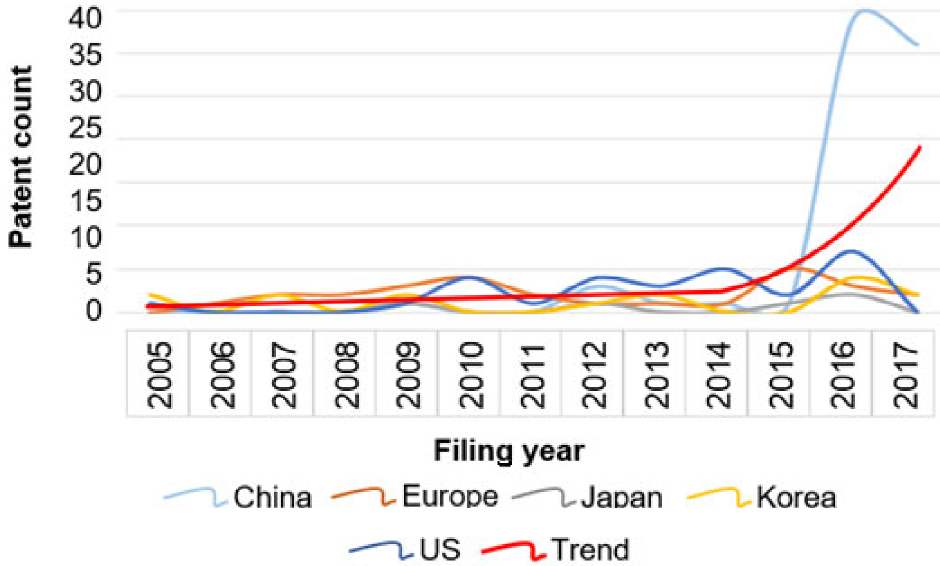

Figure 3.2 - IPR activity in bridge SHM. CN-China, EU-Europe, JP-Japan, KR-Korea, US-United including overall trendline States (source: TRIMIS)

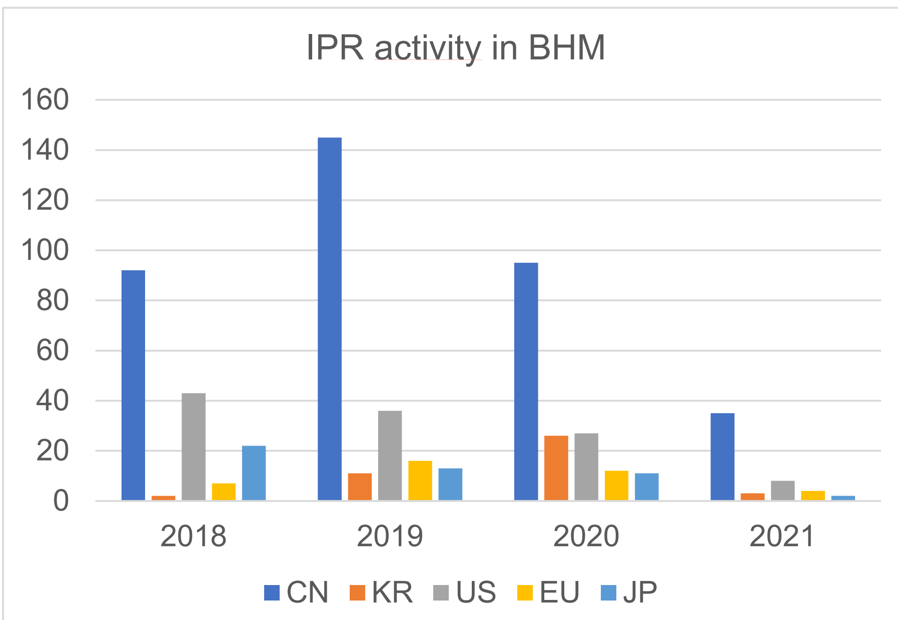

Figure 3.3 - IPR activity in bridge SHM in China, European Union, Japan, South Korea and USA (data source: TRIMIS)

Using the information provided by (Gkoumas, van Balen, Tsakalidis, & Pekar, 2021) and analysing the highlighting technologies and methods relevant to bridge management in Europe, recent examples of long-span highway bridges that were equipped with SHM sensors (Structural Health Monitoring sensors) and other instrumentation since the construction phase are found:

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- The Rio-Antirio Bridge (officially Charilaos Trikoupis Bridge) in Greece, one of the world's longest multi-span cable-stayed bridges. The bridge has a "floating" deck which needs specific monitoring actions.
- The Millau Viaduct, a multi-span cable-stayed bridge in southern France inaugurated in 2004, for which monitoring system was designed in parallel with the bridge design and was also used during the construction.

In Europe, the projects focused on bridge maintenance since the 1990's until 2019 cover the European Framework Programme 2 (FP2) until H2020 Framework Programme. According to TRIMIS, these are 51:

- FP2: Assessment Of Performance And Optimal Strategies For Inspection And Maintenance Of Concrete Structures Using Reliability Based Expert Systems
- FP3: PREC8
- FP4: BRIME; Development of a specific cable with new mechanical and corrosion protection characteristics to improve maintenance and safety of suspended bridges; MILLENIUM; SIMCES; Advanced methods for assessing the seismic vulnerability of existing motorway bridges
- FP5: IMAC
- FP6: ARCHES; CISHM; SUSTAINABLE BRIDGES
- FP7: BRIDGE; BRIDGE SMS; BRIDGE-MON; CROSS-IT; HEALCON; INSPIRE; IRIS; ISMS; ISTIMES; LONG LIFE BRIDGES; MEMSCON; NERA; OPTIMUMS; PANTURA; RAIN; REAKT; RPB HEALTEC; SAFELIFE-X; SERON; SERSCIS; SERIES; WI-HEALTH; WSAN4CIP; SHARE; SYNER-G
- H2020: AEROBI; BridgeScan; COBRI; FORESEE; FASTSCALE; INFRALERT; LoStPReCon; PANOPTIS; RESIST; SAFE-10-T; SAFEWAY; SENSKIN; Mart-Patch; WRIST; SERA;

According to (Gkoumas, van Balen, Tsakalidis, & Pekar, 2021) these projects can be categorised in the following research themes:

- Maintenance & Lifetime: this category comprises research with the improvement of maintenance procedures and lifecycle assessment as a driving force.
- Sensing Technology: any undertaking that involves the study of sensors. It excludes the use of commonly available sensors and technology.
- Software Tool: this refers to the production of software for database creation, management, and analysis of bridge and infrastructure systems.
- Bridge Safety: This section focuses on bridge safety.
- Structural Health Monitoring: requires the creation of a continuous monitoring system that detects flaws using a combination of sensors, models, and past knowledge.
- Materials & Components: this category includes research into novel materials and components for bridges that are being built or that are being retrofitted.
- Bridge Manual Inspection: this section comprises initiatives that focus on methods and technologies for inspecting the structure on a regular basis.
- Risks: research into various natural and man-made hazards.

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Figure 3.4 - Topics covered in European research projects from 1990 to 2019, based on (Gkoumas, van Balen, Tsakalidis, & Pekar, 2021)

Figure 3.4 shows that Bridge Safety, Hazards, Sensing Technology and Maintenance & Lifecycle are topics dealt within FP7 and H2020, whereas Software Tools, Materials & Components, Bridge Manual Inspection and SHM are present during all the programmes, (Gkoumas, van Balen, Tsakalidis, & Pekar, 2021).
The main findings from European projects can be summarized as follows:

- Information-based bridge management concept.
- Vibration-based SHM researches and structural identification and on-line systems-
- Monitoring of bridge cables.
- Innovative materials for bridge identification and bridge corrosion protection.
- Railway bridge upgrading to accommodate higher loads.
- Earthquake action and consequences.
- SME projects to develop close to market technologies and software.
- Use of UAVs for bridge inspection.

It is difficult to predict how widely these studies will be adopted. Besides, as will be highlighted in the needs revealed by the CoPs, a gap in the ways to leverage the measurements made with the various instruments/technologies and associate them engineering performance levels within decision-making tools and processes has been identified. On the other hand, there exist duplicities in sensor technology, as comparable sensor technologies are employed in different domains (e.g. naval, aeronautical) and for various civil structures (tall or special buildings, dams, tunnels, bridges).

The most recent projects focused on the integration of recent technologies related to bridge management are PANOPTIS (Development of a Decision Support System for increasing the Resilience of Transportation Infrastructure based on combined use of terrestrial and airbone sensors and advanced modelling tools) and SAFEWAY (GIS-based Infrastructure Management System for optimized response to extreme events of terrestrial transport networks). Moreover, MITICA (MonItoring Transport Infrastructure with connected and Automated vehicles), a 2-year Exploratory Research project but the European Commission's Joint Research Centre (JRC), will focus on indirect SHM (iSHM) of bridges from sensors present in cooperative, connected and automated vehicles that are expected to enter the roads in the future.

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In addition to these projects, there are other European projects, some of them not directly included in H2020 but related to the topic and currently in progress:

- C-ROADS: The platform of harmonized C-ITS deployment in Europe.
- 5GCarmen: 5G advances to provide a platform to support automotive sector.
- ICt4CART: ICT infrastructure to enable automation (up to L4).

It can be recognized that there is a weak link between research and wide scale adoption of surveillance technologies (more evident for smaller structures) because of the complexity of implementing new technologies in a wide scale, for this reason, the emerging technologies need to solve different challenges. The most promising solutions and technologies according to (Gkoumas K, 2019) explored to provide alternatives to traditional SHM approaches are:

- Drones
- Vision-based monitoring
- Crowdsourcing,
- Earth observation data and satellite images

Analysing in further detail the use of drones, for example, it seems that the use of UAVs (Unmanned Aerial Vehicle) for inspections is more than a trend ((Alsadik & Nex, 2021)).Thanks to their ability to perform repeated inspections, even in challenging and dynamic environments, they make it easier to monitor infrastructural changes over time. A big step has been the recent development towards autonomous inspections using conventional UAVs equipped with either image-based or Lidar-based tools. These advances can certainly reduce human error and assist in a safer, faster, more accurate inspection generating data that is accessible online. Furthermore, UAVs can perform repeated inspections even in challenging and dynamic environments, making it easier to monitor infrastructural changes over time. In general terms, the technology is currently between Level 3 (i.e. a level at which the major functions are running automatically) and Level 4 (i.e. a semi-full autonomous level), with a significant level of pilot control still required. The development of miniaturised processing units is driving higher automation by increasing the capacity for data to be processed on board the platform. However, Level 5 autonomy (i.e. a full autonomous level) has not yet been reached for UAVs and it is associated with many discussions and concerns about regulations, traffic conditions, security, safety and privacy.

In this sense, the use of UAVs in bridge inspections has a great impact compared to other conventional inspection. Usually, bridge inspection is normally performed using a snooper truck, which is a large and expensive truck that carries the inspection crew but poses critical safety risks to their lives. These traditional bridge inspections are costly, and those costs can increase significantly if interruptions occur because of problems with lane closure on the bridge. Currently, UAVs are used by many companies and contractors for bridge inspections because they are up to 75% cheaper to operate, unaffected by traffic levels, more environmentally friendly and they avoid the subcontracting costs of bridge climbers, who are costly and their activity is dangerous.

3.3 State of the standardisation

In order to establish an overview of the current state of the art as embodied by standards, guidelines and other regulations an insight into the current state of standardisation is established and presented in (e.g. (Bigaj-van Vliet, Allaix, Köhler, & Scibilia, 2021) and the following. The scope is directed on those standards that address at least partly the challenges related to maintenance, safety assessment and monitoring. There overview is focused to the following aspects:

- maintenance of bridges and tunnels,

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- assessment of existing structure,
- structural monitoring.

Despite that international standards provide definitions, principles and frameworks for asset management (e.g. (ISO 55000, 2014)) and risk management (e.g. (ISO 31000, 2009), (ISO.IEC 31010, 2019)), and European standards on maintenance (e.g. (EN 13306, 2017), (EN 15341, 2019)) have been included, decision making regarding maintenance of bridges and tunnels is mostly regulated on national and even on local level (infrastructure operators). However, the most recent national guidelines prescribe lifecycle-oriented management approaches and predictive maintenance strategies. For instance, the guidelines in the UK for the management of bridges (e.g. (CS 465 , 2020), (CS 466 , 2020) and (CS 467, 2020)) implement a risk-based approach to support decision making regarding ranking the importance of interventions and risk management measures, including maintenance. The risk assessment is based on predefined qualitative risk evaluations depending on the bridge typology, predefined lists of hazards and vulnerable structural details, qualitative estimation of the likelihood of adverse events and consequences of these events. A variety of hazards are considered in terms of material, durability and structural deficiencies, insufficient past maintenance and incomplete past assessments. Information about the structural conditions from inspections and monitoring are considered in the evaluation of the likelihood of risk events. Prioritisation of structures is facilitated by simplified risk rating indicators. While there are several guidelines focused on the maintenance of bridges aiming to ensure an adequate level of structural safety, less detailed recommendations and provisions have been found for tunnels. The reason is that maintenance of tunnels has likely to do with road safety more than structural safety.

Regarding the assessment of existing structures, the standardisation process started earlier at the national level in some countries than at the European level. As an example, the Netherlands and Switzerland developed at the beginning of last decade national standards dealing with the safety verification of existing structures. These standards have received a lot of attention in the professional community as they are seen as a major contribution to a practically highly relevant problem context.

In the Netherlands, two assessment levels are defined: disapproval and repair. The first level is used to assess if the structure is fit for use, while the second one concerns the safety in case of repairs. The reliability requirements prescribed by the Dutch standards are differentiated with respect to the assessment levels and consequence class. The differentiation with respect to the assessment levels results in lower partial factors for the actions compared to those used for the design of new structures. The reliability requirements given in the Swiss code for existing structures (SIA 269 “Existing structures - Bases”) depend on the efficiency of the interventions and the consequences of structural failure, following the approach of the Joint Committee on Structural Safety (JCSS, 2002). While these standards provide rules for updating actions and material properties, the consideration of deterioration in the safety assessment is addressed by means of generic principles. On the contrary, the British guideline “CS455 The assessment of concrete highway bridges and structures” provides detailed guidance for assessing the resistance of existing concrete structures affected by corrosion of the reinforcement or degradation of concrete. As an example, guidance is given about the measurement of the bar width and the assessment of the residual cross-sectional area of the reinforcement bars in case of corrosion of the reinforcement. With regard to the future development of deterioration, the guideline suggests to use available data, including any previous investigations and monitoring, to estimate the corrosion rate.

The most recent standardisation documents on structural monitoring consists of a limited number of international standards (e.g. (ISO 4866, 2010) and “ISO14963 Mechanical vibration

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and shock - Guidelines for dynamic tests and investigations on bridges and viaducts]), national standards (e.g. (UNI/TR 11634, 2016), RVS 13.03.01 “Monitoring von brücken und anderen ingenieurbauwerken” and GB 50982-2014“Technical code for monitoring of buildings and bridge structures) and guidelines (e.g. SAMCO guideline for Structural Health Monitoring (Rücker, Hille, & Rohrmann, 2006)). In addition, there are standards and guidelines on the use of monitoring data for supporting the management of the transport infrastructure (e.g. (CS 470 , 2020)). These standards have been analysed with respect to the following aspects:

- definition of monitoring
- objectives of monitoring
- accuracy requirements
- guidelines on the design of the monitoring system
- guidelines on data acquisition, cleansing and pre-processing
- guidelines on use of monitoring data for structural diagnostics, safety evaluation and/or asset management.

Standards and guidelines define structural monitoring as the automated, temporary, periodic or continuous observation of the condition of structures by means of sensors, while the British guideline (CS 470 , 2020) includes also visual inspection as source of information.

When referring to the objectives of monitoring, standards and guidelines mention the identification of deterioration or damage, the control of the condition of the structure in operation and providing information to support maintenance planning. Furthermore, some standards, like the Chinese guideline (GB 50982-2014, 2014) and the Austrian guideline (RVS13.03.01, 2012) include the control of the structural condition during the construction phases in the list of objectives, in particular for structural typologies or structural dimensions considered close to the limits of the scope of the current design standards.

In terms of measurement accuracy, the Chinese guideline and the (ISO 4866, 2010) provide specific accuracy requirements for specific applications and sensing technologies in terms of percentage of the full scale and in terms of the frequency resolution. Other documents, like the Italian the Italian guideline (UNI/TR 11634, 2016) and SAMCO guidelines, provide guidance on the specification of the required accuracy depending on the problem at hand and the objective of the monitoring activities.

The Italian guideline is the only document among those analysed providing a detailed appraisal of the principles underlying the design of the monitoring system. These principles include the knowledge of the structural behaviour to be monitored, the physical properties to be measured, the choice of the data analysis methodologies and the decisions that should be supported by the monitoring system.

Regarding data acquisition, cleansing and pre-processing, standards and guidelines provide generic guidelines depending on the characteristics of the monitored process (e.g. low or high dynamic processes) and the external factors that might influence the measurements (e.g. temperature, noise) or faulty measurements.

Concerning the use of the monitoring data, standards and guidelines concern mainly structural diagnostic. In this respect, guidance is given in terms of the structural parameters and indicators that are affected by damage and deterioration (e.g. modal parameters). In addition, the Italian guideline provides the explanation of the principles of model updating based on monitoring data.

Examples of publications with standards, used in individual European countries, depending on the type of monitoring are presented below.

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Country	Use	Publication
Finland	Maintenance Inspection	SILKO Guides Inspection Manual Inspection Guidelines
France	Inspection	*„Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art"* (IT-SEOA) *„Image de la Qualité des Ouvrages d'Art"* (IQOA)
	Repair	*„Choix et Application des Produits de Reparation et de protection des Ouvrages en Beton"* *„Référentiel Pour Les Produits De Réparation"* *„Mise En Peinture Des Bétons De Génie Civil"*
	Repair, Strengthening	6 AFNOR standards 1 AFGC recmendations on use of FRP
	Repairs, Products	AFNOR standards and certification reports
Germany	Inspection	**DIN 1076** *„Engineering structures in the course of roads and paths, monitoring and inspection" (Ingenieurbauwerke im Zuge von Straßen und Wegen - Überwachung und Prüfung)* **Guideline RI-EBW-PRŨF** *Recording And Assessment Of Damages (Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfungen)*
	NDT	ZfP Bau Kompendium
Norway	Inspection	**HB 147**: *„Guideline for bridge management"* **HB 129**: *„Inventory Handbook"* **HB 136**: *„Inspection Handbook"* **R411** *„Bruforvaltning riksveg (Bridge management national roads)"*
Sweden	Inspection	**1996: 35E** *„Bridge inspection manual"* **1996: 38E** *„Measurement and condition assessment of bridges"* **1996: 37E** *„Schedules of codes"* **K84289 TRVINFRA-00213** *„Inspektion av bro och övriga byggnadsverk"* **TRVINFRA-00215** *„Inspektion av tunnel och bergkonstruktioner"*
United Kingdom	Series	**BD standards** and **BA technical** notes on a range of bridge engineering topice **BD 63/17** *„Highway structures: Inspection and maintenance. Inspection. Inspection of highway structures"*
Austria	Inspection, Repair	**ONR 24008**: *„Evaluation of load capacity of existing railway and highway bridges"* Richtlinie zur Erhaltung und Instandsetzung von Bauten aus Beton und Stahlbeton **ÖNORM B 4706:2015 07 15** *„Repair of concrete structures - National specifications for products and systems for the protection and repair of concrete structures according to ÖNORM EN 1504"* **RVS 13.03.01** *„Checking and Assessment of Bridges and Tunnels, Monitoring of Bridges and other Engineering Structures"* **RVS 13.03.11** *„Checking and Assessment of Bridges and Tunnels, Road Bridges"* **RVS 13.04.01** *„General structure data and the documentation of the condition of structures, databases are created"*

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		RVS 13.04.13 *„Management of walls and anchored structures in the road network"* **RVS 13.05.11** „Calculation of Life-Cycle-Costs for Bridges"
Italy	Inspection, Monitoring	**UNI/TR 11634:2016** „Guidelines for structural health monitoring" **MIT guidelines** *„Guidelines for risk classification and management, safety assessment and monitoring of existing bridges"*
Netherlands	Inspection, Repair	**NEN 2767** *„Condition assessment built"* **CROW-CUR 117** *„Inspectie en advies civiele kunstwerken"* **NEN 3140** *„Skilled person"* **CROW-CUR 124** *„Constructieve veiligheid bestaande bruggen en viaducten van decentrale overheden"*
Poland	Inspection	**Construction Law** *„Prawo Budowlane* - Dz. U. 2020 r. poz. 1333"
Denmark	Inspection	Handbook *„Eftersyn af bygværker"*
Spain	Inspection	**ITPF-05** *„Guideline for railway bridges technical inspections"* **ADIF, NAP 2-4-0.1** „Inspección principal de puentes de ferrocarril" **ADIF, NAP 2-4-0.0** *„Inspección básica de puentes"* **ADIF, NAP 2-4-0.1** *„Inspección básica de túneles de ferrocarril"* **ADIF, NAP 2-4-1.1** *„Inspección principal de túneles"*
Latvia	Inspection	**General Construction Regulations** *„Vispārīgie būvnoteikumi - Latvijas Vēstnesis"*
Czech	Inspection	**CSN 73 6221** *„Prohlídky mostů pozemních komunikac"*
Slovakia	Inspection	**TP 08/2012** *„Ministerstvo dopravy vystavby a regionalneho rozvoja SR, 2012b"* **TP 07/2012** *„Ministerstvo dopravy vystavby a regionalneho rozvoja SR, 2012a"*
United States	Inspection	**National Bridge Inspection Standards**

Table 3-2 - Manuals and guides of relevance for malignance, safety assessment and monitoring of infrastructure

The table above shows that the subject of monitoring is being developed mainly in Scandinavian countries, as well as in Germany, France and Great Britain. In the case of inspections that are carried out on bridge structures, these are visual inspections. Newer and newer technologies allow to control components that are generally difficult to access. In such a situation, among others, drones can be used in which the camera is mounted so that it is possible to conduct an accurate vision of the lower part of the object.

The inspection is carried out with varying frequency. General inspection is the most common. On average, it is performed once a year, less frequently every 2-3 years, depending on the regional/national standards. Another type of facility inspection is principal or major inspection, which is carried out every 5-6 years. In addition, there are such inspections as: annual, routine, superficial or basic inspection. Below, Table 3-3 shows a comparison of inspections in the various countries described in the previous chapters.

Country	Inspection name	Occurrence
Germany	Routine observation (RO)	6 months
	Visibility inspection (VI)	1 year
	Elementary inspection (E)	3 and 6 years
	Main inspection (M)	6 years
	Special inspection (S)	triggered by extreme events (weather phenomenon or traffic accident)

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Austria	Ongoing monitoring	4 months
	Control	2 years
	Test	6 years
Italy	Basic inspections	6 – 24 months
	Special inspections	2 – 5 years, triggered by results of basic inspections or by extreme events
	Static load tests	
	Dynamic surveys	
Netherlands	Routine Inspection (RI)	
	Current condition (CC)	
	Future condition (FC)	
	Further Investigation (FI)	
Poland	Basic inspection	1 year
	Extended inspection	5 years
Norway	Simple inspection	1 year
	Main inspection	3 – 10 years
	Special inspection	triggered by extreme event or need for further investigations
Sweden	Main inspections	at least every 6 years
	Special inspections	when needed
Denmark	Principal inspection	1 – 6 years
	Special inspection	when needed
Spain	Basic inspections (railways)	1 year
	Main inspections (railways)	15 years maximum
	Load tests (railways)	15 or 30 years
	Basic inspections (roads)	15 months
	Main inspections (roads)	5 years
Portugal	Routine inspections	
	Principal inspections	3 – 6 years
	Special inspections	when needed
Latvia	Inspection	1 year
Estonia	Visual inspections	4 years
Lithuania	Technical inspection	1 year
	Main inspection	6 - 8 years
Czech Republic	Routine checks	6 or 12 months
	Main checks	2, 4 or 6 years
	Extraordinary checks	triggered by extreme events (weather phenomenon or traffic accident)
	Control inspections	6 years
Slovakia	Routine inspections	1 year
	General inspection	4 years
	Special inspections	triggered by traffic accident
	Visual control inspection	as a result of an emergency
France	Visual inspection	1 year
	Assessment inspection	3 years
	Detailed inspection	3 – 9 years
	Extraordinary inspection	triggered by extreme events
United Kingdom	Security inspection	1 week or 1 month
	General inspection	2 years
	Principal inspection	no more than 12 years
	Special inspection	triggered by visual inspection results
	Specific inspection for assessment	with principal inspection
United States	Routine	
	Damage	triggered by extreme events (weather phenomenon or traffic accident)
	In-depth	

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	Special	

Table 3-3 - Bridge inspections

The growing interest in the subject of structural monitoring can be observed on the example of the development of the first European standards. It is true that there is no document that would legally regulate the scope of SHM monitoring, but the standards that define the methods and procedures used to manage physical assets are being implemented ("EN 17485; Maintenance - Maintenance within physical asset management - Framework for improving the value of the physical assets through their whole life cycle").

The potential of SHM monitoring is extremely important. In its case, it is extremely important to classify the type of the structure in relation to a given damage category. This is to link the key parameters with the characterization of monitored phenomena for different categories of structures and damage classes. As an example monitoring system SHM is able to extract natural frequencies and damping ratios from the data collected. This will allow to obtain information such as durability or reliability of the facility.

SHM monitoring poses many challenges. The basic aspect is the implementation of newer and more innovative technologies. This is an extremely important factor as the current norms / laws relate to a widely available group of bridges. Individual criteria for the classification of damage to objects are not taken into account, and there is a need to treat each bridge individually.

In addition, a large part of the bridges in Eastern and Southern Europe did not get a chance for modernization recommended due to higher loads. The factor that caused this is very common, and it is the lack of financial resources. Therefore, it is extremely important to obtain them not only from EU or state funds, but also from non-governmental funds.

More frequent routine inspections will be able to preventively inform that a given element of the bridge requires modernization, thanks to which the funds needed for its repair will be much lower than in the case of repairing the entire facility. Hence, routine inspections are so important and necessary.

Another challenge is to attract a larger group of specialists in the field of SHM monitoring. Establishing a bridge certification system will improve the competences of inspectors and engineers. In addition, the training to which these people are subjected should be focused on all features of the inspection and monitoring, e.g. destruction processes, system and methods of assessment.

It is therefore essential to define robust criteria for assessing the overall condition of the bridge with a specific inspection frequency. It would also be worth considering the introduction of a common class of assessment of engineering objects, thanks to which the system would be consistent with regard to the assessment of structural damage. The implementation of appropriate algorithms for detecting damages will allow to identify, localize and then classify the deterioration processes based on the severity and location of occurrence. This would allow these failures to be integrated with prioritization techniques to better improve bridge condition modelling over time.

Unfortunately, many countries do not have specific laws that govern bridge inspection. They are mainly based on strategic management, project planning and bridge work specifications. Supervision is carried out only for the strength and viability of engineering objects. Often there is one unit missing (e.g. road management) that will be responsible for the supervision of engineering structures.

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3.4 Current challenges and needs with regard to maintenance, safety assessment and monitoring of transport infrastructure

One of the major objectives of IM-SAFE project is to reach the consensus regarding the development of new standards. Therefore, IM-SAFE has created a broad Community of Practice and is constantly evaluating the viewpoints of stakeholders. According to the meetings organised during the first year of the project with the different National Community of Practice (involving stakeholders from Italy, Netherlands, Spain, Poland, Germany, Austria, Switzerland, Norway, Bulgaria, Finland, Sweden and Denmark).

CoPs meetings celebrated during the initial phase of the IM-SAFE project has disclosed the different needs and challenges. Discussions took first place in local meetings and the preliminary conclusions had been followed up by a Pan-European CoP meeting where common denominators have been identified. In the following the identified challenges and need are summarized. More detailed and specific background information is documented in Annex A3.

3.4.1 Challenges

3.4.1.1 Lack of standardisation

The represented community of practice sees a major challenge in the lack of standardisation and consistent coverage of the entire problem complex maintenance – safety assessment – monitoring inspection. This relates to missing standardized requirements and criteria, but also to missing standards concerning methods and required assumptions. As a consequence of the lack of standardisation important assumptions and modelling choices are under the responsibility of individual experts and engineers. Safety criteria have to be defined by the infrastructure owners or have to be adapted from related standards. Lack of standardisation is also seen as a main reason for lack of confidence in the application of advanced methods for structural reassessment.

3.4.1.2 Decision-making with regard to monitoring

Monitoring is always an individual decision and the possibilities for generalisation /standardisation are limited. Monitoring (and inspection) with the objective to acquire relevant and correct information about the structural integrity, requires a sequence of decisions about the type, location, timing of measurement, and decisions about data handling and analysis. These decisions are difficult to take and require multidisciplinary expertise. At the same time, each existing structure is rather unique in terms of structural layout, exposure to loads and deterioration processes.
The CoP stakeholders see this aspect as a main obstacle to develop local guidelines and it can be seen as a major challenge for the establishment of future standards.

3.4.1.3 Handling large uncertainties

Handling large uncertainties e.g. associated to unexpected / unknown material deterioration behaviour imposes a major challenge in the process of evaluations and decision-making. Especially safety assessment is often associated with large uncertainties. The representation of these uncertainties is in general difficult. As a result, uncertainties are often ignored and the assessment is performed qualitatively which leads to highly inefficient decisions. Lack of proper uncertainty handling is also a main obstacle for the correct utilisation of monitoring / inspection data.

3.4.1.4 Prediction of required future expenses for maintenance

Prediction of required future expenses for maintenance for budget allocation is an aspect that is consistently addressed by infrastructure owners which often apply a reactive maintenance strategy, i.e. damage is detected and subsequently repaired. This leads to a situation where

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future budgets can only be guessed based on past experience and the uncertainties are correspondingly high. Standardized concepts for predictive maintenance would facilitate more accurate planning of future budget demands.

3.4.1.5 Changes in traffic load regulations.

The service live of civil engineering works in traffic infrastructure is generally estimated as 50-150 years. Traffic loads are changing during such long periods and traffic load allowances are to be increased. Such situations require a revaluation of the load bearing capacity and reliability for a large number of civil engineering works. This calls for standardised procedures.

3.4.1.6 Costs and benefits of maintenance measures

Maintenance measures are associated with higher costs and cost advantages are not evident. The advantages of optimal maintenance are safe and resource efficient operation of infrastructure. However, the optimality does not become evident in short periods and for individual structures, i.e. it seems to be possible to save money by reduced, suboptimal maintenance. Standards can help to formalize requirements for structural maintenance.

3.4.1.7 Expert knowledge on deterioration processes

Lack of engineers with the required expert knowledge on deterioration processes and reliability analysis is also a systematic feedback from the CoP. The level complexity of practical maintenance, assessment and monitoring situations is often too high to be talked by general engineers. Advance future standard can trigger education pre-graduate and practicing engineers and may trigger a major development in the profession.

3.4.1.8 Information inventory

Creating and managing a consistent information inventory for each structure and for groups of structures is major challenge to the stakeholders. Each structure should have a corresponding data base where information about the design, construction and service life are stored. Maintenance, assessment and monitoring/inspection is always taken basis in this information that is continuously updated with available evidence. Minimum requirements and standardized compatible formats for these inventories are missing.

3.4.2 Needs

The identified challenges need to be addressed in the future development of procedures and methodologies for structural maintenance, safety assessment and monitoring. A subordinate need that was expressed by the relevant stakeholders of the CoP was the creation and further development of standards that provide clear guidance for criteria and assumptions. This, in order to ensure consistency in treatment of cases within the traffic network, but also in order to create confidence among the responsible stakeholders.

In the dialogue with the CoP stakeholders it also became apparent that already ongoing local developments should be accommodated for in future standardisation. Thus, the following two general needs for future standardisation can be identified:

- Future open standards shall be open enough to ensure the integration of recent local developments towards risk-based management of infrastructure.
- Future open standards shall enable the application of advanced methods and provide for an uptake of recent and future research findings to the benefit of present and future structural maintenance, safety assessment and monitoring.

The concrete challenges that are identified above can be related to the following specific thematic needs that have been identified by the CoP's:

- Change of paradigm from reactive maintenance to predictive maintenance.
- Standardized methods for evaluating the load bearing capacity and safety of a structure.

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- Principles and requirements concerning the design of monitoring / inspection campaign.
- Standards for digitalisation in management, analysis and storage of data - Interface to BIM.
- Consistent methods for data analysis and uncertainty representation.

3.5 Main trends in current practice

Another important outcome of the dialogue with the local and Pan-European CoP's was the identification of trends for future best practices. These are:

- Trend 1: Risk-based maintenance management and condition-based preventive maintenance strategies
- Trend 2: Risk-based inspection and condition survey planning
- Trend 3: SHM with novel (non-remote) technologies: distributed sensing, wireless and energy-efficient sensor technologies
- Trend 4: Autonomous sensing incl. drone inspections
- Trend 5: Remote sensing
- Trend 6: Implementation of IoT and data analytics

Given the wide variety of practices and different level of application of the trends, it would be beneficial to share lessons learned, share the knowledge and unify the criteria, methods and regulations in Europe to assure the resilience of the infrastructures and optimize the maintenance practices.

With the purpose to go in depth in the trends ongoing in the European countries for monitoring and maintenance in transport infrastructure, the CoP have been asked to provide an appraisal of these trends. The results of these questionnaires are shown in Annex 3. Below the evaluation of the collected information is discussed per trend in more detail with an additional consideration of the relevant challenges.

3.5.1 Risk-based maintenance management and condition-based preventive maintenance strategies (Trend 1)

Aging infrastructure and the corresponding increasing number of objects that require proactive maintenance action makes this first trend a development that cannot be circumvented. In order to maintain the safety and to allocate a limited budget optimally, risk based strategies are already broadly implemented and will undergo a rapid development from qualitative to quantitative optimisation based approaches.

According to the CoPs, the main challenges in deploying this trend are:

- Lack of standardization or regulations.
- Lack of experience especially with quantitative methods.
- Lack of personnel that is qualified.

3.5.2 Risk-based inspection and condition survey planning (Trend 2)

Previously, bridge inspections were time-based. Some countries have recently started to introduce guidelines for using a risk and vulnerability analysis in order to change the inspection intervals resulting in a shift from strictly time-based inspection routine to a more condition-based inspection programme. The bridges are considered individually or may be divided into groups of similar properties and condition. Based on the condition based assessment the future inspection intervals are specified.

According to the CoPs, the main challenges in deploying this trend are:

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- Necessary short term adjustment of budget.
- Lack of standardization or regulations.
- Lack of experience with the method.
- Lack of personnel that is qualified.
- Difficult to quantify the return over the investment in short time or for individual structures.

3.5.3 SHM with novel (non-remote) technologies: distributed sensing, wireless and energy-efficient sensor technologies (Trend 3)

The technological field of structural health monitoring is rapidly evolving and the amount of data that can be acquired on structures is vast. More and more, it becomes possible to relate the acquired data to the relevant safety related load, resistance and damage variables. At the same time sensors become smaller, more energy efficient and not at least cheaper, such that this is seen as the major enabling technology for effective infrastructure management.

According to the CoPs, the main challenges in deploying this trend are:

- Quality of requirements for health monitoring.
- Lack of standardisation.
- Cost.
- Lack of software to help processing and storing data

3.5.4 Autonomous sensing incl drone inspections (Trend 4)

Drones and other autonomous devices are increasingly used in bridge inspections. They are generally equipped with cameras that enable monitoring of the condition of the facility both on the upper and side parts. Some drone models also have a camera mounted on the top of the device, allowing us to inspect the bridge from below.

According to the CoPs, the main challenges in deploying this trend are:

- Only visual parameters can be detected.
- Training of the personnel
- Sites requirements: not close to the airport
- Security measures

3.5.5 Remote sensing (Trend 5)

The present approach of manual inspection, or manual installation of monitoring devices that are based on contact and in-situ point sensing is increasingly seen as inadequate and expensive due to technical limitations and labour costs. Monitoring systems that are based on remote and spatial sensing techniques are therefore necessary to provide safe and cost-effective infrastructure management.

According to the CoPs, the main challenges in deploying this trend are:

- Integration with other systems
- Mainly use for long-term infrastructure monitoring

3.5.6 Implementation of IoT and data analytics

Modern monitoring and inspection methods create a large amount of spatially distributed data that requires proper management. The introduction of Big Data technologies and Internet of Things (IoT) into infrastructure management is seen as a major trend correspondingly. In this regard, Building Information Model (BIM) technologies are highly relevant. They are a way to represent, store and maintain object specific information that is relevant for structural maintenance and are therefore seen as an important interface between portfolio and object

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representation. For the planning and design of new standards, BIM has become a standard for data storage and exchange and the potential is seen large for the use in structural maintenance.

According to the CoPs, the main constraints to deploy this trend are:

- Lack of knowledge
- Lack of training by the users
- Ability to use by technicians
- Lack of data, multiple data systems. Only one system to integrate data is required.

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4 Future-oriented transition in maintenance, assessment and monitoring practices

4.1 Outlook to future practises

Transport infrastructure owners have to manage and maintain large portfolios of bridges. In particular, they have to ensure that these bridges are safe and do not set its users at risk or impair with the transportation performance of the traffic network. Bridges have a rather long service life and during that period doubts about the structural integrity of the bridge might arise e.g. due to increased traffic loads or deterioration process in the structural material. These doubts require the assessment of the structural reliability of the bridge.

In this chapter the correspondence between safety assessment, maintenance and monitoring is depicted and general challenges for practical implementation are discussed with special focus on decisions and assumptions that might be supported by future codes and standards. Particular attention is given to technical aspects of maintenance, assessment and monitoring where the transition towards novel approaches is most desired and likely to have the strongest impact on the future practices.

4.1.1 Demand on Structural Safety

Structures like bridges and tunnels are important elements of a functioning transport infrastructure. At the same time they bind a significant amount of financial and natural resources. Future bridge maintenance has to be directed to an optimal and safe utilization of these resources.

Bridges are generally created to fulfil a specific purpose (e.g. bridges are usually built to overcome an obstacle that separates two places in order to shorten the distance between them) while complying with various performance requirements, such as to (ISO 2394, 2015):

- Function satisfactorily under all expected actions throughout their specified service lives; providing service and functionality.
- Withstand extreme and/or frequently repeated and permanent actions, as well as environmental exposures occurring during their construction, anticipated use, and decommissioning.
- Be robust such as not to suffer severe damage or cascading failure by extraordinary and possibly unforeseen events like natural hazards, accidents, or human errors; providing sufficient robustness.

Structural performance is often assessed by so called limit state functions. Limit state functions are dividing the possible structural responses into two domains, one desirable and one undesirable domain.

If the predicted response of a structure remains in the desirable domain for the entire service life with sufficiently high probability (or reliability), the structure is considered to be safe.

For new structures, requirements on structural performance are usually assessed by means of generalized and simplified rules that are formulated in structural design standards. Structures that are designed according to these rules in the design standards are in general considered safe implicitly. Therefore, some basic assumptions from this code have to be fulfilled, as e.g. according to Eurocode 0 (EN 1990, 2002):

- Design and execution are made by skilled personnel and under adequate supervision and quality control.
- The structure is used in accordance with the design assumptions.
- The structure will be adequately maintained.

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4.1.2 Maintenance and structural safety

While requirements for safety of new structures are widely formalized and standardized the situation is different for the operational phase of structures. Sufficient safety over time is one of the objectives of structural maintenance.

Maintenance is understood as the "Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EN 13306, 2017) For bridges and tunnels the required function is the safe accommodation of a specified traffic volume over time. The associated objective of bridge and tunnel maintenance is thus related to:

- traffic safety (the expected accident rate is sufficiently low), and,
- structural safety (the expected probability of structural failure is sufficiently low).

Maintenance for traffic safety is focused on the detection of observable issues with e.g. the carriageway, guardrail, traffic signs and technical installations. If an issue is observed a suitable repair and mitigation strategy will be chosen and subsequently implemented. Regular inspection and maintenance are normally performed by the owners of the traffic infrastructure. Insufficient and unacceptable structural safety cannot be directly observed in such regular inspections. Instead, structural safety of existing structures as bridges and tunnels has to be assessed by a combination of observations from inspections and/or monitoring, tests and analysis. In contrast to criteria and procedures for the design of new structures, methods and criteria to be applied in the assessment of existing structures are far less established and standardized. In the remainder of this chapter the main technological pathways and the associated potentials and challenges for practical implementation will be introduced and discussed.

4.1.3 Assessment of structural safety of existing structures

The maintenance of sufficient structural safety of bridges and tunnels is the responsibility of the owners of the corresponding traffic infrastructure in principle. The decision whether the explicit assessment of structural safety for a bridge or tunnel at hand is necessary is also in the responsibility of the infrastructure owner and should be followed up proactively during the entire service life of the structures.
The necessity of the assessment of structural safety can become evident for several reasons that all involve detection or suspicion of deviations from design specifications or design assumptions.

If doubts about the structural safety are present, an assessment is performed, with two possible outcomes: the bridge or tunnel is considered as sufficiently safe and can be operated as before; or, otherwise, appropriate measures to restore structural safety should be implemented. Measures can be of physical nature, as strengthening and repair but also of organisational type, as restrictions for traffic. Reanalysis of the structure based on more data and/or better models is also an important possible measure, as is the surveillance of structural response by monitoring.

Assessment of the structural safety of existing structures as bridges and tunnels is a complex and demanding process that involves several stakeholders and numerous decisions have to be taken during that process. The clear and logical structure of sequence, responsibility and criteria for these decisions is of paramount importance. A general scheme is provided in Figure 4.1.

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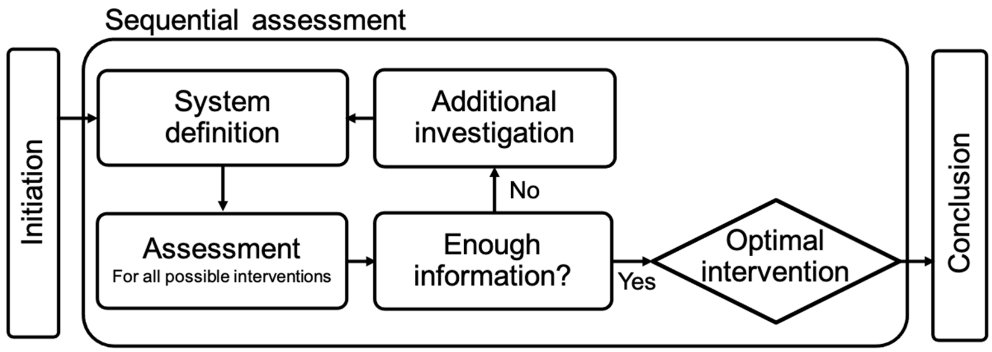

Figure 4.1 - Conceptual assessment scheme

The sequence might be structured as follows (ISO 13822, 2010) (JCSS, 2001) :

Initiation:

- Is there any reason to initiate an assessment?
- What are the criteria for initiation?

System definition:

- Collect existing information of the structure like design documentation, safety plan, service criteria agreement. If documentation is not available, necessary information has to be collected in coordination with the owner of the structure.
- What are the requirements for the structure according to load bearing and corresponding structural response according to prevailing building standards and owner specifications?
- What are load scenarios the structure is exposed to?
- What are the relevant failure modes for reliability assessment?
- Are there any exposures to damage processes?
- Is there any other relevant information available that should be utilized in the initial assessment?
- What is the intended service life time?
- Which potential physical measures for increasing safety are relevant?
- Which potential organisational measures for increasing safety are relevant?
- What relevant data could be acquired in a detailed investigation?
- The information should as far as possible be updated based on the available current information about the structure, e.g. the information that led to doubts about safety.
- What are the criteria for the assessment? What can be accepted and why?

Assessment: (sequential assessment)

- Are the doubts about the safety of the structure confirmed by simple analysis of the available information? i.e. are critical deviations from the design assumptions present, e.g. is the structure damaged?
- If yes, continue to a formal quantitative reliability assessment.
- What are the limit states for the representation of the relevant failure modes?
- What are the variables in these limit states and how can the associated uncertainty be represented based on the existing information?
- What is the reliability for the identified limit states?
- What are the consequences of the associated failure events?
- How would physical measures affect the estimated reliability?
- How would organisational measures affect the estimated reliability?

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- How would new information that could be gathered by inspections or monitoring affect the uncertainty representation and the result of the reliability analysis?
- What is the optimal combination of acquired information, physical and organisational measures?

Documentation and predictive planning:

- The assessment is documented and all assumptions, possible simplification and limitations are stated. It is concluded with a clear recommendation and an action plan. The action plan includes instant organisational and physical measures, but also recommendation on future monitoring, inspection and assessment based on the predicted future behaviour of the structure.

4.1.4 Relation between safety, maintenance and monitoring

Based on the above introduction the following intermediate conclusion can be made:

Reliability with regard to structural safety is a principal requirement for structures in general, and for bridges and tunnels in particular. It is a precondition for the functionality but also an important requirement for human safety. Requirements for structural reliability are implicitly fulfilled by following design standards. But this involves a number of assumptions about the structure and its use throughout the specified service life. **Maintenance** is intended to follow up whether these assumptions can be maintained during the service life, i.e. whether an observed deviation from these assumptions call for further analysis and corresponding mitigation action.

In this context, structural health monitoring, or simply **Monitoring**, is defined as the frequent or continuous, normally long-term, observation or measurement of structural conditions, actions or structural response (ISO 2394). Monitoring has the potential to support infrastructure owners with large amounts of data for decision making. This requires a clear definition of what information is needed to make the decision, and a strategy for acquiring and analysing data that results in useful information. **Monitoring** can have different purposes in the assessment process. It can either be seen as structural surveillance in combination with defined alarm criteria for the initiation of assessment, as information gathering for the assessment, or as a possible intervention, i.e. as implementing or extending a monitoring system as a mitigation measure.

4.1.5 Transition towards risk-based approaches to asset management

A transition towards more rational safety-oriented approaches to maintenance, assessment and monitoring requires a broad practical implementation of the procedure depicted above. This requires a challenging but necessary shift of paradigm that must be supported by corresponding standards. In the next chapter, more technical details of the different steps of the procedure are introduced and the potential for enabling transition to future practices is discussed.

4.2 Technical challenges and in assessment, monitoring and inspection of transport infrastructure

In this chapter the main technical challenges of more rational approaches to maintenance, assessment and monitoring are discussed. The order of content is thereby aligned with the procedural order that is generally taken in a reassessment situation (compare Figure 4.1), i.e.:

- Criteria for the initiation of assessment,
- System definition,
- Safety assessment,
- Information acquisition and modelling,

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- Decision making,
- Documentation.

4.2.1 Criteria for the initiation of assessment of structural safety

It is, with current available methods and resources, not feasible to continuously do structural assessment for all infrastructures in service. It is also not the goal to aim for, as many structures perform as intended and are therefore not in need for assessment. For some structures with evident deficiencies, it is instead clear that an assessment is needed. But for many structures that are somewhere in between perfect and clearly deficient, it is not obvious whether an assessment is required. Therefore, there is a need for standardization of criteria for initiation of assessment. As the number of existing structures are huge, this first screening should be simple and conservative.

In current guidelines, the reasons for initiation are situations of **detection or suspicion of deviations from design specifications or design assumptions** (in short: deviations from design). This is based on the idea that structures are designed to be safe and that any deviation from the design may adventure the safety. Furthermore, deviations should be relevant and significant, i.e. deviations should not only be detected but also evaluated and quantified. Examples are (see (ISO 13822, 2010), (JCSS, 2001)):

- Human errors in design
- Deviations in material quality
- Indirect or direct detection of damage or deterioration
- Deviations due to inadequate workmanship and quality control at construction site
- Extension of service life
- Change of use, e.g. increased traffic load
- Non-satisfactory serviceability: deformations, vibrations
- Extraordinary incidents: fire, earthquake, etc.

As is evident from the list, the reasons for assessment are diverse and they should all be covered by the specified criteria for initiation. Investigation (inspection and monitoring) can provide information for some of the aspects. Reasons related to change in operation need to be covered by asset management routines. For ad-hoc situations, the operator/owner must continuously evaluate the stream of information from different sources and identify the information that may imply deviations from design. To determine whether the deviations are relevant and significant or not, is a challenge. In this early phase, there is little structure-specific information about failure modes and associated limit states and comprised variables, i.e. it cannot yet be specified what is relevant for the structural safety. A conservative approach must therefore be taken.

Asset management is understood as coordinated activities to realize value from assets. It is a broad concept standardized in ISO 55000 that can be used across all industries. Asset management essentially involves establishing a set of performance indicators that indicate the status of the objects, to set up a quality control plan defining performance goals, and to measure and compare the performance indicators with these performance goals. However, the principles are not directly applicable to structures, as structural safety cannot directly be observed. Quantification of performance indicators and specification of performance goals for infrastructure assets varies among the European countries. This challenge was addressed in the recent COST action TU1406 “Quality specifications for roadway bridges, standardization at a European level” (Stipanovic, et al., 2017) specifically for roadway bridges. The status of roadway bridge management throughout Europe was investigated with the aim to harmonize these performance indicators and performance goals to improve the basis for establishing a

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conforming guideline. Structural reliability was concluded to be the central performance goal to be adopted for structures, but a holistic approach was suggested that also incorporate the performance goals availability, robustness, life cycle costs and environmental efficiency.

When life-cycle cost and reliability are to be addressed a risk-based inspection and monitoring framework is an essential part of asset management as the notion of risk include both reliability and costs. Current standards are focused on industry, see ISO 31000 for the general concept of assessing risk in terms of probabilities and consequences, and EN 16991 for integration of inspections into a risk framework. Risk-based decision making frameworks are available for specific assets such as bridges (Frangopol, Dong, & Sabatino, 2017), railway assets (Papathanasiou, Martani, & Adey, 2017) and tunnels (Strauss, et al., 2020).

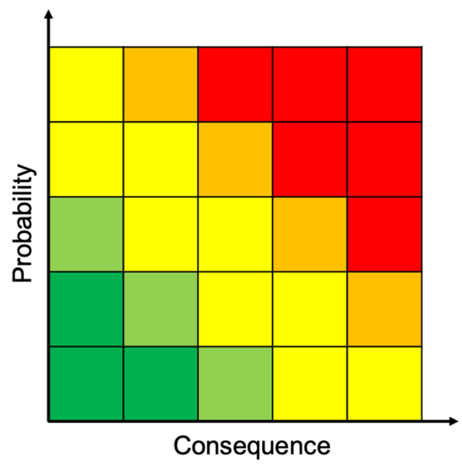

Figure 4.2 - The risk matrix is a simple but limited tool for assessing risk. Green colour indicate low risk, red colour high risk.

Inspections and monitoring may be used for evaluating the performance goal structural reliability based on condition indicators, and accordingly for initiating assessment. Typically, visual inspections are carried out on a regular basis and damages are observed and registered. Damages may be described in terms of condition indicators, i.e. by type of damage, degree of damage, type of consequence of damage and severity of consequence, as will be evident from 3 where current practices are described. This procedure may result in a simple visual representation of the risk, as illustrated in Figure 4.2. Other research projects like (PIARC, 2016), (Stipanovic, et al., 2017) and (VSS, 2014) confirm this finding and outline the short comes of this current practice of condition rating. The problems may be summarized as:

- Subjectiveness: The outcome of a visual inspection is dependent on the inspector and cannot be reproduced satisfactory.
- Accuracy: The information collected may not be relevant for the reliability, and more concerning, the relevant information may not be detected.
- Precision: The condition rating is a rating at a nominal or ordinal scale with values that have no true meaning. Therefore, it is difficult to compare different types of deficiencies with each other (e.g. cracks versus spalling).
- System effects: It is not clear how the rating for one component should be transferred to the system level (bridge or tunnel) and the network level. The representation is dependent on the size of the system which makes the interpretation of very low and very high risks problematic.

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To conclude, results from inspections are currently being used for maintenance planning and for initiating further assessment, but this approach is not accurate enough for the critical decisions to be made. Condition rating from inspections may be used as performance indicator, but the link between the rating and the structural reliability must be strengthened by more refined and targeted inspection and monitoring methods.

Monitoring may replace or supplement inspections for initiating assessment, and should be included in the criteria for initiation. This could be done implicitly, in the criteria for deviations from design, or explicitly. As monitoring is a structure-specific activity, the explicit criteria should relate the monitored parameter to a threshold for assessment specified in the monitoring plan. Compared to inspections, monitoring has potential to indicate structural reliability in more objective, accurate and precise way. As simultaneous monitoring on several locations is possible, system effects may be better incorporated.

Rational identification of structures that require structural assessment requires simple but conservative criteria for initiation. Detection or suspicion of deviation from design specifications and assumptions is a robust criteria that covers a wide range of reasons. This criterion needs to be further specified to be useful in practice. Inspections is the main activity to ensure structural safety as of today. The inspection data may be utilized for initiation of assessment as a performance indicator of the structural reliability, if used with caution. Monitoring enables continuous measurements of properties more relevant to the structural reliability.

4.2.2 System definition in context of safety and risk assessment

Safety assessment has to be seen relative to the corresponding context and the assumptions that are made. It is therefore of importance to define both carefully and this is in general called system definition.

The system definition must contain all information and specifications that are relevant for the safety assessment. As the level of detail of analysis may increase during the assessment, the requirements on the system definition might also change, i.e. the system definition has to be adapted with increasing level of detail.

The system as addressed here does not only contain the physical assets of concern, i.e. the load bearing structure of bridges and tunnels. It also contains loads that the structure is exposed to, the corresponding functionality and all direct and indirect consequences that are associated to the different possible present and future states of the structure, i.e. states like damage, collapse, etc. Safety assessment is to be seen relative to possible safety measures and is formulated as a decision problem among those. Therefore, the stakeholders and their preferences as well as all possible alternatives for safety measures are also part of the system.

For the specific context of the intended safety assessment the representation of the system has to be defined such that:

- it represents the physical and/or procedural characteristics of the considered assessment problem, as well as the spatial and temporal characteristics of possible events and the corresponding consequences,
- it facilitates a safety assessment and corresponding ranking of specified decision alternatives/mitigation measures, which is consistent with available knowledge about the system and which facilitates that the results may be updated according to knowledge which may be available at future point in time.

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The definition of the system requires a large number of "modelling decisions" that are crucial for the validity and for the feasibility of the structural assessment. It requires information, experience (and acceptance) from several experts and stakeholders relevant to the context of the structural assessment, and it is common to formalize information gathering and "modelling decision making" in meetings or workshops (risk-screening).

The following aspects are relevant for the system definition and should be thoroughly addressed and documented:

Definition of decision maker and other stakeholders.
The decision maker and other stakeholders should be identified and the corresponding preferences should be defined. The laws, rules and standards that apply to the situation at hand, and the corresponding criteria to comply with shall be explicitly addressed. The objective and acceptance criteria for the safety assessment should be formulated.

Definition of temporal and spatial boundaries.
Temporal boundaries include the time periods to be considered, i.e. the residual service life or time until the next assessment.
Spatial boundaries include the object(s) as well as the geographical area for which the consequences are considered.

Hazards.
General identification of the hazards to be dealt with in the analysis. This might include loads, accidents, natural hazards, damage and deterioration processes. Here it is also important to specify what is not considered in further analysis.

Direct and indirect consequences.
Consequences that are associated with physical damage and/or loss of integrity and loss of functionality of the system. The system constituents (components) that may be damaged or fail when exposed to a hazard are to be identified. The relation between the joint state of system constituents (components) to system functionality, or loss of system functionality has to be represented. Damage, failure and loss of functionality should be related to the preferences of the decision maker. Preferences of the decision maker might be expressed either in risk (monetary units), minimum reliability or compliance to other safety related criteria.

Measures/decision alternatives.
The general selection of possible measures must be determined together with the decision-maker. A distinction must be made between two general types of measures:

- Measures that lead to a change in the state of a system, i.e. physical or organisational.
- Measures that increase the knowledge about the system and enable a better representation of the system.

Uncertainties.
The relevant variables and processes of the assessment have to be identified and represented conditional to existing information. Special emphasis on dependencies / correlations / common cause effects. Assumptions and simplifications are often necessary but should be clearly stated in the system definition.

New information.
The available and potentially available information that might be relevant for the safety assessment should be identified. The decision space may be extended with a selection of relevant sources of new information that are specified in terms of the expected effect of the new information on uncertainty reduction together with the costs of the new information.

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The above list does neither represent a sequential nor a hierarchal order. The different aspects have similar importance and should rather be addressed iteratively in order to arrive to a system representation that facilitates a reasonable safety assessment.

Available information in the design specification

In structural design, system definition is often called design basis and for usual structures rather generic and standardized procedures are followed and many of the herein introduced aspects are only considered implicitly. For exceptional structures, however, the development of a design basis is very similar to system definition.

Available documentation about the structure is obviously to be considered and correspondingly updated during the system definition.

4.2.3 Reliability analysis in context of safety and risk assessment

An essential part of safety assessment is the estimation and analysis of the likelihood of the events that are associated with consequences that have been identified in the system definition. These events might relate to damage, component failure, structural collapse or similar. This analysis can be referred to as a reliability analysis.

The reliability analysis can be performed on different levels of detail with respect to the physical representation of the events of interest and in regard to the treatment of information and the consideration of uncertainties. The choice of the level of detail is of crucial importance and should be done carefully and based on rational criteria. The assessment of how sensitive the outcome of the reliability analysis is against marginal alteration of the modelling level of detail might be considered as a valuable guidance.

It is also considered good practice to envisage a consistent level of detail in modelling the physical event and the corresponding uncertainties.

A common principle of reliability analysis is that the possible structural responses are assessed and divided into two domains consisting of desirable and undesirable states. The boundary between these domains is called the limit state and entering the undesirable domain is defined as failure. It is then distinguished whether reliability is assessed explicitly or implicitly.

4.2.3.1 Explicit reliability analysis

Quantitative reliability analysis takes basis in the estimation of the probability of adverse events. Adverse events are defined by limit states. Based on quantitative reliability analysis, the assessment decision is chosen such that it complies to a predefined reliability requirement, e.g. formulated in terms of an acceptable failure probability.

Where analytical models for the representation of adverse events or failure events are available, the limit state can be represented by the function and the time variant basic variables $\boldsymbol{X}(t) = X_1(t), X_2(t)$so that,

$$g(\boldsymbol{X}(t)) = 0 \tag{1}$$

Equation (4) is the limit state equation, and

$$\Omega(\boldsymbol{x}(t)) = \{g(\boldsymbol{x}(t)) < 0\} \tag{2}$$

identifies the domain of adverse or failure events $\Omega(\boldsymbol{x}(t))$.

The computation of the probability of failure takes basis in all available knowledge, and the uncertainty representation includes all relevant causal and stochastic dependencies as well as temporal and spatial variability. Here simplifications are often necessary for practical purposes. The appropriate level of simplification as well as the choice of method for the calculation of the failure probability depends on the characteristics of the problem at hand.

Depending on the characteristics of the problem, it might be allocated to one of the following types reliability problems:

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- If a single failure mechanism is to be analysed and its occurrence probability does not depend on the point in time or space the time-invariant reliability analysis is chosen.
- If a single failure mechanism is to be analysed and its occurrence probability does depend on the point in time the time-variant reliability analysis is chosen.
- If several failure mechanisms have to be considered simultaneously, the system reliability analysis is chosen.

4.2.3.1.1 Time invariant analysis

In case the reliability problem addresses a single failure mode and does not depend on time (or spatial characteristics), or may be transformed such that it does not, e.g. by use of extreme value considerations, the fundamental structural reliability problem is generally formulated as

$$P_{f,T} = \int_{\Omega(\mathbf{x})} f_{\mathbf{X}}(\mathbf{x}) d\mathbf{x} \quad (4)$$

Where $\mathbf{X}$ is the vector of basic random variables, $\Omega(\mathbf{x}) = \{g(\mathbf{x}) < 0\}$ is the failure domain defined with limit state function $g(\mathbf{x})$ representing the considered failure mode and $f_{\mathbf{X}}(\mathbf{x})$ is the joint probability density function. In a time-invariant reliability analysis, time variable loads are represented by the probability distributions of their extreme values per reference period T. The validity of the necessary assumptions in regard to ergodicity and independence is critically assessed. If there is more than one time-variable load involved, they are combined, taking into account the dependencies between the loads.

So called structural reliability methods are used for the computation of the failure probability by Equation (4). Depending on the problem at hand, one of the following methods is selected:

- First order second moment method (FOSM)
- First/Second order Reliability Method (FORM/SORM);
- Simulation techniques, e.g. Monte Carlo simulation, importance sampling, asymptotic sampling, subset simulation, and adaptive sampling;
- Numerical integration.

The reliability index per reference period T, β_T and the probability of failure per reference period T, $P_{f,T}$ are the standard metrics to express structural reliability. Both metrics are related as follows.

$$P_{f,T} = \Phi(-\beta_T) \quad (3)$$

where $\Phi(.)$ is the standard normal cumulative probability distribution function.

4.2.3.1.2 Time variant reliability analysis

If the reliability problem cannot be simplified to a time-invariant problem, a time-variant reliability analysis is performed.

In a time-variant reliability analysis, it is often of interest to predict the time to the first failure, or the probability of failure in a specified time interval. For both problems the average out-crossing intensity is of interest (see e.g. (Melchers & Beck, 2018)).

4.2.3.1.3 System reliability analysis

If a failure event to be considered depends on the interaction and dependency of more than one single failure mode, system reliability analysis is necessary. Correspondingly, system failure event is defined as a combination of failure modes. (for details see e.g. (Thoft-Christensen & Baker, 1982)).

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4.2.3.2 Implicit reliability analysis

In many practical engineering situations, uncertainties and probabilities are not explicitly considered. Instead, generalized and simplified deterministic formats are used. These formats are often calibrated based on explicit reliability analysis and are therefore usually called semi-probabilistic formats.

In semi-probabilistic analysis an assessment decision is chosen such that it complies with the criterion that an assessment value of a resistance is larger than an assessment value of a corresponding load effect. Assessment values for the load bearing capacity r_a are chosen to have a sufficiently low non-exceedance probability and assessment values for loads e_d are chosen to have a sufficiently low exceedance probability such that the assessment criterion, if calibrated, in the limit $(r_a = e_a)$ corresponds to the required level of reliability.

In the so-called load and resistance factor format (Ravindra & Galambos, 1978) assessment values are estimated based on characteristic values and partial safety factors γ as e.g. $r_a = \frac{r_k}{\gamma_M}$ for resistance variables and $e_a = \gamma_E\, e_k$ for the effects of applied loads. Both, the definition of the characteristic value and the choice of partial safety factor, is made in order to meet the reliability requirements. However, the correspondence to reliability requirements is generally made for domains of assessment situations for which generalized assumptions in regard to consequences and uncertainties are made.

With semi-probabilistic design, structural performance on a component/failure mode level can be assessed. The explicit consideration of the interaction of failure modes in a structure, i.e. system effects, is not accommodated for.

Semi-probabilistic analysis is the predominant method for structural design and is outlined in (ISO 2394, 2015). Executive guidance and standardization is found in several national and international design standards as, e.g. the Eurocodes.

4.2.3.2.1 Correspondence between explicit and implicit reliability analysis

The level of detail of the reliability analysis has to be chosen such that it best supports the objective of the safety assessment. The ability to account for the particular conditions of a specific assessment situation and therefore identify a more optimal assessment decision is increasing with an enhanced level of detail. That is the reason why explicit analysis can be used to verify or calibrate approaches for implicit analysis. However, the complexity and difficulty are increasing with the level of detail and from a standardization perspective, i.e. where a unified set of rules and assumptions for broad application shall be standardised, implicit semi-probabilistic approaches are advantageous since their inherent low level of detail goes along with the allowance for broad generalization.

Assessment situations as compared to design situations are much more difficult to generalize as each existing structure is quite particular in terms of load history, deterioration state, available information, etc. Thus for assessment situations it is much more difficult to identify a reasonable level of generalization/simplification. That might lead to the conclusion that higher level explicit reliability analysis is more suited for the assessment of existing structures than implicit analysis, i.e. semi-probabilistic methods following e.g. the partial factor format.

4.2.4 Integration of information from Inspection and Monitoring

Safety assessment of a structure can be supported by collecting (measuring/ monitoring/ inspecting/ testing) information (through indicators) about the state of the structure. Sometimes information about indicators are not only collected specifically by a discrete in time inspection but also continuously by monitoring.

Observations acquired by inspection and monitoring inform about the safety of the structure and can be explicitly utilized to update the reliability analysis.

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Referring to explicit reliability analysis, information from inspection and monitoring can be utilized for inference on the representation of one or several random variables X_i, or for inference on the representation of failure probability directly.

For the type of information, it can be differentiated between so-called equality type and inequality type information. Equality type information is corresponding to measured variables and inequality type information denotes the information carried with a measurement that some variable is greater than or less than some predefined limit. It can also be differentiated between direct and indirect information; i.e. direct measurements of the quantity of interest and the measurement of some indicator of the quantity respectively. Examples for the different types of information are given in Figure 4.3.

	direct	indirect
equality	load measurment	chloride content
inequality	proof-loading	status inspections

Figure 4.3 - Examples for the different types of information

So-called Bayesian inference is used for updating random variables. Accordingly, the information contained in inspection or monitoring data $\boldsymbol{z}$ can be introduced by the Likelihood function $L(\boldsymbol{x}|\boldsymbol{z})$ which connects the observation z to the property of interest X. The Bayes' rule can then be applied to compute the updated probability density of X as:

$$f_{X|Z}(x|z) = \frac{L(z|x)f_X(x)}{C}$$

$f_X(x)$ is the probability density prior to updating and C is a normalization constant.

There should always be a clear reason for implementing a monitoring system. According to (Vardanega, Webb, Fidler, & Middleton, 2016), the following aspects should be considered when adopting a monitoring strategy (the aspects will be examined in detail in next stages of the IM-SAFE project):

- Overall objectives of monitoring
- Identification of information needed from monitoring to fulfil the objectives
- Accuracy and frequency needed for decision making
- Suitable technologies for acquiring the data
- Suitable methods for analysing the data
- Value of information

In research, the objective for monitoring is usually deviating from the bridge owner's needs and the results are not to be directly used for decision making for the monitored bridge. (Webb, Vardanega, & Middleton, 2015) present a monitoring classification system with five categories, and indicates the value for the asset owner for each category, see **Error! Reference source**

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not found.. Sensor deployment studies include demonstration of new sensors or communication technologies, which may lead to future developments of technologies valuable for asset managers, but do not provide immediate value. Damage detection, i.e. identification of type, location, extent and/or rate of damage, usually by modal analysis of the vibrational response of the structure or vision-based methods, has high potential value as it can be integrated into the structural assessment. The other monitoring categories are also valuable for asset managers as they are linked to the structural assessment process. Anomaly detection and threshold check can be used for initiation of assessment and as possible interventions, were the threshold check is more valuable as it is directly related to the performance model. Model validation may be used for calibrating the model used when evaluating the limit states.

Category	Description	Value for asset owner
1	Sensor deployment studies	No immediate value
2	Anomaly detection (detection of change, no model)	Limited value, may initiate further assessment
3	Model validation (comparison of model and actual performance)	Little immediate value, increase confidence in structural performance
4	Threshold check (performance criteria determined from model, action upon alarm)	High value as directly linked to performance criteria, but the performance criteria are difficult to establish
5	Damage detection (structural identification, modal analysis)	High value but difficult to achieve

Table 4-1 - Monitoring categories (Webb, Vardanega, & Middleton, 2015)

4.2.5 Decision-making based on safety assessment

The fundamental purpose of assessment and any associated activity is to establish information for decision support. For that purpose the results of the safety assessment have to be presented to the decision maker together with all assumptions and simplifications and relative to criteria that relate the results either to formal standard or legal requirements and/or to benchmarks that are established from experience.
The evidence that can be drawn from the safety assessment is thereby dependent on the on the corresponding level of detail.

- Based on qualitative or implicit reliability analysis, no explicit safety criteria can be assessed. Possible mitigation and/or repair measures are identified based on experience / tradition.
- Based on explicit reliability analysis, compliance to an explicit safety criterion formulated e.g. in terms of a target reliability index can be verified. Mitigation and/or repair measures are planned based on evidence for insufficient safety and the effect of the measures can also be analysed.
- Based on risk analysis, the consequences can be integrated and the optimal mitigation and/or repair measure can be identified. The effect of more information on the optimal decision can also be quantified.

For decision making the decision maker takes all the information to his disposal and attempts to identify the decision alternative that satisfies his/her preferences best. Besides the criteria that can be deducted from the formal safety assessment aspects that might influence the final decision are as follows:

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- risk aversion,
- political aspects,
- budget constraints,
- traditions and experience.

The technical safety assessment and the corresponding risk-based evaluation of decision alternatives is therefore only one of several aspects that trigger the final decision. How the holistic treatment of the above-mentioned factors is treated consistent to the preferences of all stakeholders is to be specified in the context of future standards.

4.2.6 Archiving and future planning

In the previous sections we have seen how an assessment evolves from a potential initiation to a sequential assessment, incorporating more information and more advanced analysis, until an optimal assessment level is reached. Regardless of the level of detail reached by this procedure, the results should be reported and used for future planning. This section outlines aspects of this documentation phase, in order to make the most out of the investments into assessment.

In general, because of the complexity of the assessment process, the result is very much dependent on the assumptions. In a sense, the reliability is not a property of the structure itself, but rather an outcome of the analysis. Therefore, clear and consistent documentation of assumptions and limitations is essential. This also means that the amount of documentation will increase with refined assessment.

For the first step, initiation of assessment, crude performance indicators at ordinal or nominal scale may be used. These are efficiently reported in an asset or Bridge Management System (BMS) that collects, stores and presents all information about important characteristics of the asset, as well as results from inspections over time. When the detail of the assessment increases, it is no longer sufficient to report performance indicators, instead, a report with a qualitative description is more appropriate. However, a report is not a flexible system for information, and attempts are done to extend the BMS to incorporate more sophisticated information. The vision is to use Building Information Modelling (BIM) for handling multidimensional data and, by including prediction models that are continuously updated with new information, to create a digital twin. This vision aligns well with monitoring, as the data obtained from monitoring is immensely bigger than the simple condition ratings. WP4 will investigate these digitalization technologies in order to enable efficient use of monitoring data and WP3 will explore the principles of information management, highlight what knowledge is relevant for the structural assessment and maintenance planning.

All these aspects are to be addressed in the planned transition towards future practices and should be supported by corresponding standardisation.

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5 Uptake of research findings and practical applications

5.1 Analysis of Opportunities

Monitoring and inspection provide information on the state of structures and can support the assessment and prediction of the infrastructure's safety and thereby facilitate the planning of preventive and corrective actions. (Straub, et al., 2017) Sensor technology, data transmission and processing have developed rapidly in recent years. Correspondingly, more and more bridges and tunnels are equipped with monitoring systems. Infrastructure owners and operators are focusing their attention on the utilization of the collected data and are particularly interested in the cost-benefit ratio of the monitoring systems. The underlying questions are: How can I utilize the information from these systems for safety assessment? What is the value of the information provided by the measurements? The answers to these questions depend on (Straub, et al., 2017):

- the future usage and performance of the structures and associated costs and benefits,
- the inherent capabilities of monitoring and inspection system and the data processing,
- the expected outcomes of the monitoring and inspection and
- the future decisions associated with those outcomes, in particular on maintenance, repair and rebuild actions.

All these questions would be explicitly addressed in a risk-based assessment of the structures. However, because of the associated complexity of risk-based assessment, they are in practice mainly addressed on a qualitative level, regularly in a rather ad-hoc manner.

In principle, Bayesian decision analysis offers a framework for risk-based assessment (Raiffa & Schlaifer, 1961), (Straub, Value of information analysis with structural reliability methods, 2014). However, the direct implementation of the theoretical framework requires a complete probabilistic modelling of the structural performance, demands and the probabilistic integration of the information from monitoring or inspection. As a consequence, the strict implementation of the theoretical framework for risk assessment of structures has in practice been implemented only for special cases with limited complexity and good availability of models, such as the planning of inspections in offshore structures (Pedersen, Nielsen, Riber, Madsen, & Krenk, 1992), (Faber, Sørensen, Tychsen, & D., 2005). A small number of publications have recently demonstrated the applicability of the theoretical framework on idealized structural systems (Faber & Thöns, On the value of Structural Health Monitoring, 2013), (Konakli, Sudret, & Faber, 2015). These studies provide useful insights but are not directly transferable to practice because of the necessary simplifying assumptions adopted. A key question is thus how the theoretical frameworks can be used to benefit the safety assessment of real-world structures and infrastructure systems. This necessitates capturing the complexity of the asset management process, without making the modelling overly demanding (see e.g. (Zonta, Glisic, & Adriaenssens, 2014)).

5.2 Outlook to the Future Standardisation

Structural maintenance, safety assessment and monitoring are currently subjected to national regulations that do not follow consistent and rational approaches for safety assessment and decision making. Safe and more effective structural maintenance requires common European standards that define common general approaches, leading ultimately to the achievement of comparable safety levels and the effective use of financial and environmental resources in the EU Member States. The introduction of new European Standards should also facilitate the

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integration of digital solutions into asset management systems currently adopted by infrastructure owners and operators allowing them to benefit from the newest technological innovations. The goal of newly developed standards should therefore be:

- To close the gaps in the actual national and European guidelines and standards with respect to inspections, monitoring and testing aiming at data-informed diagnostics of structures, evaluation of the actual and future structural safety and optimisation of risk-based and condition-based maintenance strategies.
- To allow for a pro-active maintenance of bridges, tunnels and other relevant transport infrastructures.
- To include provisions for structural monitoring and for condition-based and risk-based maintenance of transport infrastructures.
- To include an amendment to the existing EU standards on safety assessment taking into account inspections, monitoring and testing.

The anticipated developments should anticipate the implications of the new standards for public and industrial stakeholders in Europe, and to generate an adoption plan and a change management strategies to secure a smooth transition from the current practice, supported by a plan for pilot cases of the future standards.
The developments should also address and harmonise standardisation efforts by the relevant European and international standardisation organisations in the disciplines of structural engineering and ICT, especially the open standardisation of Building Information Model (BIM) for civil/transport infrastructure, Semantic Linked Data for Europe's road asset management aligned with the policy of CEDR, and Internet of Things (IoT) in relation with sensing and data acquisition systems for monitoring of transport infrastructure.

5.3 Implications for the IM-SAFE workplan

5.3.1 Monitoring techniques (WP2)

A comprehensive description of the required research is defined and planned in the corresponding task descriptions of WP2, and includes.

- to review data collection technologies used for condition survey incl. devices and platforms,
- to review data analysis methods used in condition survey,
- to evaluate data collection technologies and data analysis methods used for condition survey in relation to the identified barriers,
- to identify requirements for data collection technologies and data analysis methods used for condition survey to be considered in guidelines and standards,
- to evaluate the methodologies and instruments currently available for diagnostics of structures, incl. damage detection, actions evaluation and identification of system limitations (model updating parameters),
- to identify the required technical guidance to incorporate the available data collection technologies and data analysis methods in diagnostics of structures.

Beyond the specifications of required research and documentation for T2.1 – 2.2. the following aspects should be considered in WP2:

- For each considered surveying technology specify the physical property measured and quantify measurement uncertainty.
- For each considered surveying technology specify the structural property of interest that may be related to the physical property measured. Emphasize on the probabilistic description of this relation in form of e.g. a likelihood function.
- Report on strategies for design of monitoring and/or inspection in terms of spatial arrangement and timing.

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- Consider this design process as a sequence of decisions and emphasize on the criteria and assumptions on which these decisions might be taken.

5.3.2 Datahandling and digitalisation (WP4)

A comprehensive description of the required research is defined and planned in the corresponding task descriptions of WP4, and includes:

- generating an overview of the procedures and the output of data acquisition using various measurement devices and sensing technologies to collect measurement data; and specifying interfaces for monitoring and scanning data,
- consolidating the requirements for fast and secure data transmission from on-site to data centres/platforms; data mining, visualising, cleaning and post-processing of the data; storing, managing and sharing the data for monitoring, analysis and decision-making purposes; and possible adoption of new technologies,
- proposing guidelines for the structured acquisition of data sets through scanning technologies; evaluation of cost/benefit with respect to different acquisition approaches; and integration of as-built scan data with digital as-planned and maintenance data (digital twin), both on a document-level (multi-model-containers) as well as per-object-levels (clustered point clouds, image sections),
- proposing guidelines for data processing at sensor level, with a stress on the reliability of the measurements,
- developing criteria for the successive surveying campaigns for updating the sensors,
- creating a comprehensive insight into the latest developments in open standards for interoperability of IoT data (through the measurement devices and sensing technologies) and BIM / IFC of the transport infrastructure assets,
- clarifying the advantages of the standardised Linked Data approach and semantic ontologies for EU national road authorities (NRAs) gathered in the European Directors of Roads (CEDR) as developed in the CEDR-INTERLINK project, as well as the EU geospatial open standards INSPIRE, for specific use in monitoring and risk analysis,
- outlining the possible implementation of the CEDR-INTERLINK 'Modelling and Linking Guides' to link different types of data with established as well as new semantic classifications / ontologies for use by human and machine (for example: ontologies regarding the damage classifications),
- defining the generic design for a platform / common data environment (CDE) for transport infrastructure, including the definition of: user groups of the platform and the User Experience [UX] requirements for these relevant target groups (engineers, decision-makers, etc.); what data the platform should handle; which functionalities / tools the platform should facilitate; and which requirements are prioritised for access and data sharing,
- creating an overview of relevant existing and prototype data platforms / CDE for the construction sector as studied or developed in EU research projects (such as DigiPLACE) as well as commercially available off-the-shelf (COTS) solutions,
- defining requirements and preconditions for openness, neutrality and future-proofing of the platforms, also addressing API for developments, vendor-neutrality, etc.,
- identifying the relevant aspects for data structuring and data analytics, and to generating an overview of options to deal with these aspects,
- developing complete use case scenarios that leverage AI for accelerating and automating visual inspection processes, such as detection of defects on concrete, metal or other materials, as well as assessment of civil infrastructure health,
- developing complete use case scenarios that leverage AI for automating monitoring and risk assessment of transport infrastructure, based on a wide range of sensors and measurements,

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- developing criteria for adoption of AI by domain experts with limited know how in Machine Learning: model reliability requirements, easiness of utilisation and system to enable engineer to teach and train models based on engineering inputs,
- clarifying the relevant methods of analytics, including Machine Learning, Hybrid AI, and other methods and anticipated future developments.

Given the low level of standardization and consistency with regard to data handling and digitalization it is recommended to approach the problem sequentially from a simple and basic data handling standard with correspondingly low threshold for implementation. Here basis should be taken in already existing bridge management systems and how they can be extended and standardized in order to allow for efficient maintenance management.
Subsequently, the more detailed and advanced aspects as defined in the corresponding task descriptions should be addressed.

5.3.3 Structural assessment (WP3)

A comprehensive description of the required research is defined and planned in the corresponding task descriptions of WP3, and includes:

- appraisal of currently available methods for safety evaluation and risk management
- formulation of the basis for the framework for including information from diagnostics of structures, based on data from inspection, monitoring and testing, in safety evaluation and risk analysis
- proposing a practical decision-making process for asset owners and operators to facilitate proactive maintenance, that overcomes the current barriers and reflects on the most recent developments of condition survey technologies, with the aim to reduce the risks of sudden collapse and to minimise the lifecycle cost of asset management while ensuring the required service level and quality of the infrastructures are achieved.
- developing background information and practical guidance material as rationale for the mandate for new standards (CEN) for maintenance and control of large infrastructures.
- showcasing the application of the decision-making process in relevant a real-case scenarios on the TEN-T corridors or regional transport networks.

Within this scope, special emphasis should be directed to:

- Criteria for the initiation of assessment,
- Procedures for the consideration of new information for safety assessment on different levels of detail, discuss the required assumptions and generalizations,
- Correspondence and consistency between the assessment methods on different levels of detail,
- Different safety criteria for the different levels of detail of assessment,
- Requirements on models for the different inspection and surveying technologies.

5.3.4 Standardisation (WP5)

- A comprehensive description of the required research is defined and planned in the corresponding task descriptions of WP5, and includes identifying the gaps in the actual national and European guidelines and standards with respect to inspections, monitoring and testing aiming at data-informed diagnostics of structures, evaluation of the actual and future structural safety and optimisation of risk-based and condition-based maintenance strategies.
- collecting the technical input for EU standards for inspection, monitoring and testing, safety assessment, proactive maintenance of bridges, tunnels and other relevant transport infrastructures.

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- Preparing the input for the mandate for CEN that comprises 1) new standard on structural monitoring; 2) new standard for condition-based and risk-based maintenance of transport infrastructures; and 3) further amendment to the existing EU standards on safety assessment taking into account inspections, monitoring and testing.

Within this scope, special emphasis should be given to the aspects identified in sections 5.3.1 and 5.3.3.

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6 Conclusions

6.1 Future of the monitoring and maintenance practices across Europe

For maximal safety, availability and cost-effectiveness of transport infrastructure, a paradigm shift from corrective maintenance towards risk-based/predictive maintenance through data-informed decision-making is necessary. This should be enabled by new set of harmonised European standards for maintenance, safety assessment and monitoring. The new standards should be supported and implemented coherently by the public authorities and the industrial stakeholders across Europe.

Recent technological developments have the clear potential to support these developments. The most promising are already taken up by local communities and they have been identified as major trends for development.
It is expected that future development is triggered by the development of corresponding future orientated standards that both, take up established and proven best practices and at the same time open up for the full exploration of the existing potential of the technological developments in engineering and data technology.

The following trends applied in Europe have been identified by relevant stakeholders during local and Pan-European workshops of the established Community of Practice (CoP):

- Trend 1: Risk-based maintenance management and condition-based preventive maintenance strategies
- Trend 2: Risk-based inspection and condition survey planning
- Trend 3: SHM with novel (non-remote) technologies: distributed sensing, wireless and energy-efficient sensor technologies
- Trend 4: Autonomous sensing incl. drone inspections
- Trend 5: Remote sensing
- Trend 6: Implementation of IoT and data analytics

The questionnaires analysed in the section 3.4 can give an idea of the level of application of the new monitoring and maintenance practices. Table 6-1 shows a summary of the different levels of application of the trends analysed according to the questionnaires sent to the CoP.

It can be concluded that there are big differences in the level of application of each trend depending on the country. In fact, there are no homogenies, except from some trends as BIM (which is in a standardization phase in almost all the countries) and remote sensing and autonomous sensing (which are in a pilot phase). The same result is outlined in terms of regulation since then each country has different regulations with specific inspections, periodicity, training, etc. not even similar in some cases. The necessity of having common practices and sharing the know-how with regard to the application of trends is supported by the analysis developed in this questionnaire.

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Trend	*Austria*	*Bulgaria*	*Finland*	*Germany*	*Italy*	*Netherlands*	*Norway*	*Spain*	*Switzerland*
Risk based maintenance	*S*	*NE*	*P*	*R/P*	*P/R*	*R*	*P*	*P*	*P*
Risk- based inspection	*R*	*X*	*S*	*P*	*S*	*S*	*S*	*P*	*P*
SHM	*S*	*X*	*S*	*P*	*S*	*P*	*P*	*P*	*P*
Autonomous sensing	*P*	*P*	*P*	*P*	*P*	*S*	*S*	*P*	*R*
Remote sensing	*S/P*	*P*	*P*	*P*	*P*	*S*	*P*	*P*	*P*
Cathodic Protection	*S/P*	*NE*	*P*	*S*	*NE*	*S*	*S*	*S*	*X*
IoT/BIM	*S/P*	*R/S*	*R/S*	*P/S*	*P/S*	*S*	*S*	*P/S*	*P*

*NE: Not Envisaged yet; R: Research; P: Pilot; S: Standardised; X: lack of awareness

Table 6-1 - Summary of the level of deployment for each trend according to CoP questionnaires

6.2 Proposition of future actions in context of standardisation

The development of new European standards for maintenance, safety assessment and monitoring of the structures, including the additional rules to be supplemented in the structural design codes (Eurocodes) is built upon the following major thematic areas:

- Reliability requirements for existing structures.
- Representation of deterioration processes.
- Data acquisition based on monitoring and inspection.
- Data informed safety assessment.
- Data storage and management.
- Decision making and predictive planning.

The standards to be developed are expected to have a large positive impact and will lead to safer and more efficient management of civil engineering works in the traffic infrastructure.

In the dialogue with the CoP stakeholders it became apparent that already ongoing local developments should be accommodated for in future standardization.
Thus, the following two general needs for future standardization can be identified:

- future standards shall be open enough to ensure the integration of present developments towards risk-based management of infrastructure, and,
- future open standards shall enable the application of advanced methods and provide for an uptake of recent and future research findings to the benefit of present and future structural maintenance, safety assessment and monitoring.

The success of the standards to be developed is depended on carful considerations during the development. Accordingly, the following proposition for future actions is given:

- The need for new and advanced standards must be communicated to the relevant stakeholders. Therefore, awareness campaigns should be initiated – in general through all dissemination and communication channels, and in particular among the

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CoP members. The goals of this activity are: to raise the awareness about the necessity to develop and adopt the new standards; to identify and remove the PEST barriers related to different stakeholders; and to motivate decision-makers in the public and commercial organizations to improve the knowledge and skills of their employees about the new standards.

- A plan for sound transition towards new methodology is established and clearly formulated. This will include the development of guidelines for an adoption plan based on the knowledge resulted from the different thematic domains, i.e. monitoring, structural assessment, data handling, and discussions with relevant stakeholders. The guidelines will focus on strategy development covering all relevant areas, e.g.: building further on the operational experience; step-by-step development and specification of the innovation, including digitalization strategies concerning BIM, asset management, LCC; and process management in working groups with internal and external experts.
- The pilot setup recommendations are developed and will include e.g.: combination of practical applications, their step-by-step development and the gradual integration into the implementation of the new standards; organisational development and change process to increase acceptance; further development of the software tools; and education and training of employees to become experts.

6.3 Complementary insights from best practices analysis

Infrastructure owners and researchers have acknowledged the societal relevance and the large potential of efficient inspection, assessment and maintenance of structures as bridges and tunnels. This has led to a large number of documented case studies that demonstrate solutions, potentials but also challenges that are related to the topic. The following complementary insights can be drawn from the study and analysis of these best practices conducted in curse of IM-SAFE research based on cases gathered in IM-SAFE online best practice guide:

- All selected case studies document a structural assessment situation. However, a large scatter can be observed with regard to the level of detail and comprehensiveness of the studies. Some of them attempt for a full risk-based decision analysis, some of them feature a reliability analysis and other focus entirely on the analysis and representation of measurements, i.e. without any qualitative conclusion on the structural performance. This could be interpreted such that the authors of the case studies had quite variable objectives and criteria for the assessment. The corresponding implication for future standardization is clear; criteria and objective for a structural assessment must be clearly defined and stated at the beginning of each documented analysis.
- The definition of structural performance criteria in terms of limit states is a challenge. Existing structures might be exposed to damage or degradation mechanisms that might extend the set of relevant failure modes compared to new structures. The consideration of system effects might also be more important as compared to new structures. An implication for the future development of best practices is that probabilistic methods – that can in principle account for system effects – should be favoured over semi-probabilistic partial safety methods.
- Information from measurements during inspection and monitoring is of large importance for the assessment. But the sensible consideration of this information requires functions that relate the outcome of the measurements to variables that are represented in the limit states. These functions are difficult to formulate in general. The aspect becomes particularly challenging, when spatial variability is considered relevant. That part of the analysis often requires reasonable assumptions and simplifications. Guidance on how to do these, would be highly relevant to develop.

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Specifications and recommendations of future guidelines and standards can help to overcome the highlighted challenges and might lead to a more consistent treatment of a highly complex and difficult problem setting.

6.4 Complementary insights from analysis on barriers and lessons-learned

In curse of IM-SAFE research, the existing Political, Economic, Societal and Technological (PEST) barriers to establish the agreement in the development and implementation of new standards in structural maintenance, safety assessment and monitoring of the transport infrastructure have to be defined and possibly released (see preliminary analysis given in (Bigaj-van Vliet, Allaix, Köhler, & Scibilia, 2021) and detailed the analysis given in (Hoff, et al., 2021)). Accordingly, the following external factors that could impact standardization are addressed in a PEST analyses:

- **Political** aspect of PEST analysis focuses on the areas in which factors such as e.g. (local, regional, national or international) government policy and/or changes in legislation may affect standardisation.
- **Economic** aspect of PEST analysis target past, current, and future economic issues, e.g. cost, financing (both public and private), insurance, taxes, economic growth, inflation and recession.
- **Social** factors that may be considered include socio-cultural elements such as attitudes and shared beliefs of end-users (society), policymakers and other stakeholders, and their resistance against changes.
- **Technological** component of PEST analysis considers the specific role and development of technologies, access to existing technological solutions, skills of professionals, research, innovation and emerging technologies.

The consideration of the outcomes of PEST analysis is relevant for the definition of a strategy to develop and adopt new European standards. As evident from (CEDR WG3.5, 2018), in the absence of harmonised standardisation, monitoring, assessment and maintenance of transport infrastructure is addressed by national guidelines or recommended best-practices, and a significant change is expected to take place if new Pan-European standardisation is introduced. The main objective of the PEST analysis is to provide the conditions for wide societal acceptance and commitment for the new standards among the important and relevant stakeholders in all European regions.

The PEST analysis has been developed in several steps and considering: current regulations and current practices, research and development projects viewpoint of stakeholders with a professional profile that corresponds to the scope of analysis and with experience and knowledge that provides a reliable and professional perspective on the subject area. The following examples, included in (Bigaj-van Vliet, Allaix, Köhler, & Scibilia, 2021), illustrate barriers for the establishment of agreement for the development and implementation of new standards in maintenance, safety assessment and monitoring of the transport infrastructure):

Political:
Lack of funding allocation from government may pose barriers due to public finance rules, leading to c*onsequences and related challenges* such as cutting the budget on maintenance of existing infrastructure. Constructing new infrastructure receives more political credit and exposure than maintenance of existing structures may pose *barriers* to maintenance investment, leading to *consequences and related challenges* such as maintenance backlog.

Economic:
Economic policy based on "Doing nothing is cheap" may slow down decision-making, leading to *consequences and related challenges* such as delay of the important

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maintenance actions and decisions, to the point where they cause large negative impacts such as infrastructure failure. Economic policy base on “Lowest-cost contracts” for maintenance may result in directive approach task specification in maintenance contracts, where the asset owners specify what work will be done and how it will be done, providing little or no flexibility to the contractor in its selection of means and methods.

Social:
Hierarchical / flat organizations and the effect on responsibility for individuals may lead to organizational *barriers* and *consequences and related challenges* due to lack of responsibility. As infrastructure failures are rare and therefore the perception of the risk is not rational, irrational allocation of resources/attention may take place (*consequences and related challenges)*.

Technical:
For different technologies entering the market, main *barriers* may be posed by the resistance against new technologies, leading to *consequences and related challenges* such as lack of the implementation of the efficient technologies. Lack of government spending on technological research may create *barriers* as it may lead to lack of the arenas for innovation and hinder development of new technologies/methods for monitoring, safety assessment and maintenance

The PEST analysis helps identifying the uncontrollable factors that may affect development and acceptance of standardisation. The input from the stakeholders is utilized for the enrichment of knowledge from the report by EC DG MOVE (MOVE, 2019) and other important publications on foresight studies in the diverse national settings and in the EU context.

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Annex 1 Infographics

Infographics 1 – IM-SAFE overall concept

Infographics 2 – IM-SAFE Community of Practice

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Annex 2 Current practices, needs, challenges and trends per country

A2-1 DACH (Germany, Austria, Switzerland)

A2-1.1 Current practices (Germany)

In Germany, the current regulations for engineering structures such as bridges or tunnels can be divided into three major areas:

- Design
- Construction work
- Maintenance

The part Design contains all the rules and regulations that are required for the design process, such as the guidelines for the preparation of building design (RAB-ING), the Indicative drawings (RiZ-ING) and the guidelines for planning decisions for tunnels.
The part Construction work is intended for the regulations governing construction. This includes all additional technical contract conditions (ZTV), all technical delivery conditions and technical test regulations (TL / TP) and the information sheet for construction supervision (M-Bü-ING).
The part Maintenance contains all the regulations for building inspection and monitoring and the instructions for road information database for engineering structures: subsystem building data (ASB-ING).

- **Inspection and monitoring of bridges and tunnels**

  For many decades, the basis for the maintenance of engineering structures has been regular inspections and monitoring in accordance with DIN 1076 "Engineering structures in the course of roads and paths, monitoring and inspection" in conjunction with the "Guideline for the uniform recording, assessment, recording and evaluation of the results of building inspections according to DIN 1076 (RI-EBW-PRÜF) (Infrastruktur, 2017) ". All essential processes are regulated here so that a realistic assessment of the condition of the engineering structures can be carried out and documented by skilled engineers. Due to the "close-to-hand" examination of the structures, the structure examination plays a decisive role in the safety structure of the engineering structures.

  The inspections of the engineering structures are carried out by the municipal building authorities of the German federal states, mainly by their own specially trained personnel. However, the increasing downsizing in public authorities and new political requirements are increasingly leading to outsourcing. In order to continue to guarantee a high quality of the engineering structure inspection, attention must be paid to the qualifications of the personnel to be employed when outsourcing. DIN 1076 stipulates that "The inspection must therefore be entrusted to a competent engineer, who can also assess the static and structural conditions of the structures". To ensure this, it is imperative that only personnel with the necessary education, training and experience with regard to engineering structure inspections are employed.

  The BMVBS (Federal Ministry of Traffic, Construction and City Development) supports the quality control measures for external engineering structure inspectors in cooperation with the BASt (Federal Highway Research Institute) and the road construction administrations of the German federal states. The document "Building inspection according to DIN 1076 - meaning, organization, costs" is provided for this purpose. This describes in detail the implementation of engineering structure inspections, the different types of inspections,

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evaluation criteria, building monitoring, documentation or the requirements for the inspection engineer. Furthermore, BASt offers certified training and advanced training courses in which engineers are prepared for the tasks and quality assurance of engineering structure inspections and monitoring.

With the increasing load on the bridge structures, the structure inspection has also changed over the decades. While a visual inspection with the help of a checking hammer was sufficient in the past, today a wide range of non-destructive and low-destruction checking methods are used for engineering structure inspections and property-specific damage analysis. In the case of particular damage to the structures, monitoring methods are also used more and more frequently in order to be able to intervene in good time if the damage to the structures progresses. In the future, the instrumentation of structures with "intelligent" systems such as lane crossings can provide useful support for the maintenance.

- **Execution and documentation**

  According to DIN 1076, the following examination services are to be carried out for the inspection of engineering structures:
  - Setting up the workplace (e.g. setting up traffic safety, commissioning the access technology and lighting, precautions to ensure occupational safety)
  - Instruction, coordination and control of all those involved in the inspection of the engineering structure
  - Execution of the engineering structure inspection
  - Record of the defects and damage found, draw up of sketches and photos

  The damage found during these inspections is documented and assessed according to criteria of stability, traffic safety and durability. This is followed by a transfer to the "SIB-Bauwerke" software system. Considering the extent of the damage as well as the number and severity of the individual damage, this software determines a status grade for the structure or sub-structure examined. A distinction is made between six different status grade areas:
  - 1,0 - 1,4 - very good condition
  - 1,5 - 1,9 - good condition
  - 2,0 - 2,4 - satisfactory condition
  - 2,5 - 2,9 - adequate condition
  - 3,0 - 3,4 - insufficient condition
  - 3,5 - 4,0 - poor condition

  If a structure receives a status grade above 4.0, it is immediately closed to traffic while the inspection is still in progress. Measures are then taken promptly in order to return to a state range between 1.0 and 4.0. The condition area describes how urgently repairs and renovations must be planned on the structure. A bridge with a condition rating of 4.0 (poor condition) is open to traffic and can be crossed safely. Restrictions, for example due to a maximum permissible axle load, are possible.

  If the cause of the damage or the extent of the damage cannot be sufficiently determined by the inspector, a further investigation according to the guideline "Object-related damage analysis (OSA)" is to be carried out as a rule.

- **Inspection types**

  As already described, the basis of building tests is DIN 1076. This is divided into five different types of inspections:
  - Routine observation (RO)
  - Visibility inspection (VI)
  - Elementary inspection (E)

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- Main inspection (M)
- Special inspection (S)

These differ in their scope of services and in the time intervals to be carried out. The following figure shows the inspection types defined in accordance with DIN 1076 and their implementation cycles.

Inspection type	**Inspection before acceptance of the service**	**Number of inspections up to the statute of limitations for claims for defects**					**Number of inspections until the end of the useful life**						
						Inspection before the expiry of the limitation period for claims for defects							
	Construction year	1	2	3	4	5	6	7	8	9	10	11	Farther
Routine observation[1]		2x	2x	2x	2x	2x	2x	2x	2x	2x	2x	2x	2x
Visibility inspections		1x	1x		1x		1x	1x		1x	1x		1x[2]
Elementary inspection				•					•				Every 6 years
Main inspection[3]	•					•						•	Every 6 years
Special inspection		By order or after major storms, floods, traffic accidents or other events that influence the existence of the structures											

[1] Routine observation as part of the route control and additional 2x / year observation of all components from the traffic / terrain level
[2] Except in the years when a main or elementary inspection is taken
[3] Different regulations apply to wooden bridges according to RI-EBW-PRÜF

Table A2. 1 - Inspection types defined with DIN 1076

- **Main inspection**
  The first main inspection is to be carried out before the acceptance of the construction work, the second main inspection before the expiry of the limitation period for the warranty. Subsequently, a main inspection must be carried out every sixth year for civil engineering structures.
  During the main inspection, all parts of the structure that are difficult to access must be checked close to hand. If necessary, this must be carried out with the aid of inspection facilities, scaffolding or inspection vehicles. Covers of structural parts (e.g. protective hoods for ropes, bearing sleeves, protective sleeves, manhole covers etc.) must be opened. If necessary, the individual structural parts must be carefully cleaned before this inspection so that hidden defects and damage can also be found.
  In the inspection report, the defects and damage are to be marked, which are to be checked again in the following "Elementary inspection" or in shorter periods of time. This applies in particular to such defects and damage that, individually or in total, may affect the stability, traffic safety or durability in the foreseeable future.

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- **Elementary inspection**
  The "Elementary inspection" is a comparative inspection with respect to the main inspection and must be carried out three years after a main inspection. The inspection is carried out, if justifiable, without the use of inspection facilities or inspection devices, as an intensive, extended visual inspection. Functional parts (e.g. bearings, joints, transition structures) and anchoring of components (e.g. protection against accidental contact, noise barriers, pipes) must also be included.
  For the elementary inspection, the results of the previous main inspection must be considered, and the defects and damage identified in the associated protocol must be checked.
  If critical deficiencies and damage or indications of significant changes compared to the last inspection report are found during an elementary inspection, this must be wholly or partially expanded to the scope of the main inspection.

- **Routine observation**
  According to DIN 1076, all engineering structures are to be continuously monitored as part of the general monitoring of traffic routes with regard to traffic safety. This is done as part of a route control. The "Routine observation" takes place twice a year and must be carried out on all components without special support of inspection facilities or inspection devices. All obvious defects and damage are to be observed from the traffic level and the terrain level. These are only logged if there is a risk to stability or traffic safety.

- **Visibility inspection**
  All engineering structures must be inspected once a year for obvious defects or damage. The inspection takes place without major support such as inspection vehicles or scaffolding but using inspection facilities available on the structure (accessible cavities, maintenance corridors, traffic level ...). The years in which a main or elementary inspection is carried out are excluded from the inspection. In particular, the following are to be recorded:
    - unusual changes to the structure,
    - Significant defects/damage to and lack of traffic signs, protective devices and fall protection devices,
    - Significant defects/damage and contamination of drainage facilities and transition structures,
    - significant defects/damage to surfaces,
    - considerable impact damage and concrete spalling, noticeable cracks,
    - apparent deformations and displacements of the structure,
    - Defects/damage to embankments,
    - Scouring and landings in water.

- **Special inspection**
  According to DIN 1076, a "special inspection" must be carried out after major events that affect the condition of the engineering structures, or if it appears necessary after the structure monitoring. The scope of the examination results from the special inducement. This applies, for example, to floods, accidents, earthquakes and other extraordinary events.
  A special inspection does not replace a "main inspection" or "elementary inspection"

A2-1.2 Current practices (Austria)

In the field of building management, there are various guidelines in Austria for the procedure and documentation for the maintenance and monitoring of buildings.
The main standards and guidelines relating to bridge assessment and maintenance are described below.

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- **ONR 24008**
  ONR 24008 deals with the maintenance of existing road and rail bridges. It regulates the procedure for evaluating the load-bearing capacity of bridge structures in order to identify a possible impairment of reliability.
  This standard defines under which circumstances there is a need to evaluate the load-bearing capacity. As a result, it is determined which points should be included in a status report. These points are, among other things, material characteristics and material tests, specifying the appropriate procedure for determining these properties.
  Furthermore, with regard to the condition assessment of bridge structures, a number of possibilities, in particular the arithmetic verification, but also the qualitative assessment of the load-bearing capacity, are shown. As an essential part of a structural assessment, ONR 24008 also lists the required content of a documentation of such an assessment.

- **Richtlinie zur Erhaltung und Instandsetzung von Bauten aus Beton und Stahlbeton**
  The guideline issued by the Austrian Construction Technology Association for the "maintenance and repair of buildings made of concrete and reinforced concrete" also plays an important role in carrying out inspections and monitoring on bridges.
  As in ONR 24008, this guideline defines procedures for the condition assessment and damage assessment of structures. In the appendix, various possible damage to concrete and reinforced concrete are described in terms of their condition levels (1-5), which make it possible to make a statement about the condition of the material on the basis of the data collected.
  A main part of the guideline deals with repair measures and the various possible cases of damage.

- **ÖNORM B 4706**
  ÖNORM B4706 essentially deals with the maintenance and repair of concrete structures. It describes how to determine the state of the structure with the help of various methods for examining concrete, such as inspection by visual inspection, testing by tapping, cracking, etc.
  Other essential topics in ÖNORM B4706 are the planning and execution of maintenance measures. In order to be able to determine whether measures are necessary, limit values for damage cases such as carbonation and crack formation are specified.

- **RVS 13.03.01**
  Monitoring optimizes the maintenance planning of structures in terms of time and economy. For this reason, it is advantageous to incorporate monitoring into the life cycle management of buildings.
  For this reason, (RVS13.03.01, 2012) has the "Monitoring of bridges and other engineering structures" as its content, in which the objectives, the process sequence and the types of monitoring with regard to place and time are described. The subject of measurements in relation to the measurement system, the planning and implementation of the measurement and the measured variables are dealt with in detail.
  In addition, some examples of possible applications for monitoring are listed and explained in more detail with reference to the respective cases, the goals, measured variables, the type of sensor, the type of measurement as well as the measurement method and the application limits. You can find application examples such as crack widths, deformation behavior, vibration measurements, fatigue, etc.

- **RVS 13.03.11**

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RVS 13.03.11 (BfVIuT, 2011) specifies the manner in which bridges in the course of roads and paths are to be monitored, checked and checked with regard to reliability and traffic safety.
The ongoing monitoring (every four months) as well as controls (every 2 years) and tests (every 6 years) must be carried out at regular intervals.
During controls, the change in the state of preservation compared to the last test is recorded and evaluated. The components to be examined are precisely defined in the RVS and the defects and changes to the individual components (substructure, superstructure, bridge equipment) to be identified are listed.
The state of preservation is ascertained and assessed during inspections. The following components are examined here:

- Substructure
- Superstructure
- Surface layer
- Bearing
- Waterproofing and drainage
- Edge beams
- other equipment

The findings of the test should document the following results:

- the status of the object and components
- the usability of the traffic route
- Defects or damage detected
- Required and recommended actions
- Initiate an inspection if any defects or damage found could not be determined with sufficient accuracy
- Instructions for the next inspection
- Special tests to be carried out and static recalculations
- Time of the next test (year)

The objects and components are assessed using a grading system from 1-5, whereby the grades are described as follows:

• 1 - very good condition: no or little damage, no limitation of load-bearing capacity, usability and durability
• 2 - good condition: minor, slight damage, no restriction on load-bearing capacity and usability
• 3 - sufficient condition: moderate damage, no limitation of the load-bearing capacity
• 4 - poor condition: severe damage, currently no limitation of the load-bearing capacity
• 5 - poor condition: very serious damage, reduced load-bearing capacity and/or usability

- **RVS 13.04.01**

For the administration of general structure data and the documentation of the condition of structures, databases are created. These serve as the basis for economic and technical decisions regarding the setting of measures for buildings.
The exact structure, content and required functions of a database are specified in RVS 13.04.01. In order to be able to work efficiently with the data in the database, it is necessary that the existing object information can be easily accessed. For this reason, properties are assigned to the individual objects so that they can be called up according to filter criteria. In the case of bridge objects, the description is based on the material of the superstructure, the geometry and spans, the type and construction of the cross-section, the prestressing, the bridge class, the load limitation, etc.

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- **RVS 13.04.13**
  RVS 13.04.13 deals with the management of walls and anchored structures in the road network using the structure database dealt with in RVS 13.04.01.
  Among other things, this guideline specifies a list of data to be entered that should describe the component to be tested. As a further point, the RVS describes which elements and damage to the component are to be examined. All test results and measures are defined in the RVS and are to be added to the database accordingly.

- **RVS 13.05.11**
  The maintenance costs are an essential component of the life cycle costs (consisting of construction costs, maintenance costs and demolition costs) of structures. Since the consideration of the entire life cycle costs is becoming more and more important, RVS 13.05.11 (BfWFuW, 2017) describes a forecast model for determining the costs over the entire life cycle of a building. This forecast model enables, among other things, the determination of the future budget for maintenance and renewal as well as cost transparency across all life cycle phases.

A2-1.3 Needs and challenges (Germany and Austria)

CoPs meetings celebrated during the first year of IM-SAFE project has disclosed the different needs and challenges of each country. Although, some of them, have common points, the different focuses to these aspects are considered important for a general understanding.

Challenges

- Choosing the optimal monitoring method is difficult, requires advanced knowledge of providers and various monitoring methods and their advantages and disadvantages.
- The structural engineer is the primarily decisive person with regard to the strength and remaining useful life of bridges and tunnels.
- Maintenance measures are associated with higher costs and cost advantages are not foreseen.
- In case of vibration analysis/monitoring the durability of the sensors is not secured, no permanent safeguard. Also, the comparative vibration analysis at a later point in time is difficult.
- Building monitoring is always an individual decision.
- Use of several databases, e.g. status database and master database (two separate systems).
- Every bridge is unique, it is very expensive to customize the solution.

Needs

- Methods for evaluating the supporting structure.
- Assessment of critical infrastructure and their remaining useful life.
- Predictive maintenance (maintenance, updating and tracking of the model).
- Interface to BIM.

A2-1.4 Trends (Germany)

The main trends in Germany are summarized referencing a key research project which encompass the different trends such as: data collection, digitalization, predictive maintenance, etc. : Smart bridges (BASt)

- **General concept**
  The Federal Ministry of Transport and the Federal Highway Research Institute (BASt) launched the project cluster "Smart Bridge (Intelligente Brücke)" in 2011 with the goal of designing and further developing the necessary components for such a system: an

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adaptive system that provides relevant information for holistic assessment. To put it another way, new monitoring technologies will be used to detect damages earlier than they are now (and the react timely with low-cost repairs). As a result, the bridge should become "intelligent" in the sense that it will be aware of its current state and prospective flaws.

The intelligent sensors and the complex modelling are the primary components. These necessitate sophisticated communicating sensor networks, new bridge-structure-adapted sensors, and self-sufficient energy supply systems. Detail structural and damage models, as well as reliability-based evaluation methodologies, are equally crucial.
The concept of the "Smart Bridge" is also applicable to new constructions: technological components can be considered during the planning process, and the structure can be followed during its full life cycle.

With a variety of research projects, the components of the "Smart Bridge" are currently being developed. The BASt is supported by the interdisciplinary collaboration between universities, research institutes and industry partners (BASt, s.f.).

- **Overall conception and role in maintenance management**
  The "Smart bridge" - modularly adaptable systems for the acquisition and holistic evaluation of relevant information about changes in impact and resistance in real time.

  The overall concept of the intelligent bridge includes the following elements:
  - powerful sensors for recording effects and component reactions
  - intelligent measurement data processing for plausibility checks, data fusion and data reduction
  - Holistic assessment procedures using damage and structural models as well as probabilistic approaches
  - Interfaces to an extended maintenance management

  The "Smart bridge" concept (BASt, s.f.) is geared towards both new and existing structures. The technological components can be taken into account while designing the bridges in the first example, allowing the structures to be followed throughout their full life cycle. In contrast to new structures, an extensive assessment of the condition is required for existing structures in order to provide a credible condition assessment and prognosis in real time.

- **Linking the intelligent bridge and maintenance management enables the following:**
  - Direct recording of the individual impacts and structural reactions in order to be able to derive actual hazard potentials in real time.
  - Analysis and evaluation of the structure in real time in order to inform operators and users at short notice and to be able to initiate measures in good time.
  - Reliability analyses to ensure availability during the service life.
  - Supplement to the existing maintenance management. Optimization of the maintenance planning by monitoring the aging behaviour and the temporal development of damage patterns.
  - Monitoring of usage conditions and verification of the effectiveness of conservation measures.

  Reference for the data processing scheme at the intelligent bridge is the Schema zur Datenverarbeitung from BAST:
  https://www.intelligentebruecke.de/ibruecke/DE/Konzeption/konzeption_node.html

- **Projects for practical testing and further feasibility studies**
  duraBASt - demonstration, investigation and reference area of the Federal Highway Research Institute

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Since 2016, several components of the "Intelligent Bridge" have been developed and tested on a two-span prestressed concrete bridge in the duraBASt area. This entails the installation of cutting-edge sensors on the structure to record load-bearing capability and durability characteristics. The investigations add to the BASt's already completed and continuing research initiatives on data collecting, data processing, and modelling to assess bridge condition using sensor systems (component-integrated sensors and wireless sensors).

- **Smart bridges in the digital test field highway**
  In Germany's digital test field Autobahn, important components of the intelligent bridge were implemented for the first time on a bridge. The digital test field highway, located on the A9 between Nuremberg and Munich, was established by the Federal Ministry of Transport and Digital Infrastructure (BMVI) to test procedures and applications related to "Mobility 4.0" and make them publicly accessible. As part of the focus on "digital infrastructures", a two-lane prestressed concrete replacement structure at the Nuremberg motorway junction (BAB A3 / A9) was equipped with the following relevant components of the Smart bridges: "System for impact analysis", "Instrumented lane crossings and warehouses" and "Sensor networks". A five-year test program has been in place from the beginning of 2017 to demonstrate and examine the functionality of the entire system and individual components. The object-related load model is updated on a regular basis, and the remaining service life of the bridge and its components is assessed. The modules used and the overall system are further developed in various departmental research projects (BASt, s.f.).

- **Sensors**
  In principle, the sensor systems of the Smart bridges should enable the acquisition and forwarding of relevant measured variables (possibly already selected) both for new buildings (e.g. integral sensor systems) and for existing structures (e.g. mobile sensor systems). A link with energy self-sufficient concepts is desirable.
  The following measured variables with regard to effects and component reactions are relevant:
  Actions
    - Pollutants (e.g. chlorides)
    - Humidity, temperature
    - mechanical effects from traffic, wind and temperature (both static and dynamic)

  Component reactions
    - Change in pH
    - corrosion
    - Deformations / elongations
    - Vibrations, cracks, subsidence
    - Detachment of layers
    - Loosening of fasteners

  Areas of application for sensors in this sense are:
    - Safety-relevant, highly stressed components
    - Components that significantly determine the load-bearing behaviour of the structure (e.g. ropes, prestressing, concrete in the shear area)
    - Components that have certain deficiencies
    - Components susceptible to wear and tear or damage (e.g. sealing and covering, roadway crossing construction)
    - Constructive elements, the failure of which leads to further damage to other components (e.g. surface protection systems, joints, seals)

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- Components that cannot be checked or can only be checked indirectly as part of the visual building inspection (e.g. seals under coverings)
- Components whose reactions provide important information with regard to the behaviour of the entire structure (e.g. bearings)
- Components whose reactions provide important knowledge with regard to the effects on the overall structure (e.g. roadway crossing structures, bearings, ropes)

Important framework conditions with regard to the sensors are:

- Durability requirements (e.g. alkaline environment in concrete),
- Energy self-sufficiency, power supply to the bridge is rarely guaranteed,
- Consideration of the construction site situation ("user friendliness"),
- Data transmission should be wireless,
- Serviceability,
- Possibility to monitor the functionality,
- Taking into account that the components are not always accessible,
- System redundancy (partial failure must not lead to failure of the entire system),
- Protection against vandalism.

- **Intelligent measurement data processing**

For the further use of sensor data in damage and structural models, the generation of resilient, very error-minimized status information is essential. A powerful system for sensor data monitoring and analysis, which is connected upstream of further data processing or use, makes a significant contribution to this. Adaptive and self-learning algorithms can be included to increase performance - model-based and statistical methods (artificial intelligence methods) can be used to support this.

The main tasks of such a system are:

- Plausibility of sensor data, through the detection of sensor signal errors caused by failure, aging, various interference influences that predominate in the instrumentation structure such as line crosstalk, interference from electromagnetic fields, drift; Quality statements are possible.
- Fusion of sensor data, (Merging and information integration) of the same or different measurement or recording variables for the determination of building or component-related status statements.
- Interpolation of sensor data, as input variables of program-based damage prediction algorithms, temporal and spatial interpolation to generate plausible data streams, required among other things to suppress sensor signal errors.
- Derivation of higher-quality information (automated), on selected condition parameters with the aim of independently recognizing events with previously defined metrological or building-related information content.

Reference for the data pre-processing methods at the intelligent bridge are:
The Methoden der Datenvorverarbeitung from BAST:
https://www.intelligentebruecke.de/ibruecke/DE/Konzeption/Messdatenverarbeitung/messdatenverarbeitung_node.html
The Schema zur Messdatenverarbeitung bei der Intelligenten Brücke from BAST:
https://www.intelligentebruecke.de/ibruecke/DE/Konzeption/Messdatenverarbeitung/messdatenverarbeitung_node.html

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A2-2 Italy

A2-2.1 Current practices

The current standards in Italy aim at defining the methodologies for identifying the state of existing structures, with main focus on bridges (railway and roads).
In particular, the MIT guidelines “Guidelines for risk classification and management, safety assessment and monitoring of existing bridges” (MIT, 2020) outline a procedure for the safety of existing bridges to prevent inadequate levels of damage and UNI/TR 11634 identifies design criteria for monitoring systems on the basis of classes and structural types for which such systems are recommended. MIT guidelines are focused on existing bridges, while UNI/TR 11634 includes indications that are applicable, with appropriate adjustments, to other types of structures. The UNI TR 11634: 2016 standard and the MIT Guidelines also provide indicative information on the analysis process and on the reference models available.

A2-2.1.1 Bridges in roads and railways

The general trend involves carrying out inspections at fixed intervals (eg quarterly / four-monthly/ half-yearly / ad hoc inspections on specific problems) and with different levels of detail (visual inspections, in-depth inspections). Based on the inspections, maintenance activities are therefore planned.
In MIT guidelines (2020) a general multilevel approach has been introduced, which starts with a simple census of the works of art to be analysed and arrives at the determination of a class of attention on the basis of which, in the cases envisaged by the methodology itself, a structural safety assessment will be carried out.
The complexity and therefore the cost of the inspections, investigations, controls, monitoring and checks to be carried out, is calibrated by assessing each time, in an approximate and qualitative manner, the actual need and urgency according to the current state of the work.

- **Level 0**: census of main characteristics by collecting the available information and documentation.
- **Level 1**: execution of direct visual inspections and the expeditious survey of the structure and the geo-morphological and hydraulic characteristics of the area.
- **Level 2**: definition of the class of attention of each bridge, based on the parameters of dangerousness, vulnerability and exposure, determined by processing the results obtained from the previous levels. Depending on this classification, one of the following levels is then used.
- **Level 3**: preliminary assessments in order to understand, together with the analysis of the type and extent of the instabilities detected in the inspections carried out at Level 1, whether it is necessary to proceed with in-depth investigations through the execution of Level 4 checks.
- **Level 4**: detailed assessment.
- **Level 5**: applies to bridges considered to be of significant importance within the network, appropriately identified. For these works it is useful to carry out more sophisticated analyses of the interaction between the structure and the road network to which it belongs and the consequences of a possible interruption of the bridge serviceability on the socio-economic context in which it is located.

The MIT guidelines “Guidelines for risk classification and management, safety assessment and monitoring of existing bridges” comprises the following key aspects:

- **Level 1:**
  Level 1 of the multilevel approach involves carrying out visual inspections of all the structures present on the territory and catalogued in the Level 0 census.
    - Scope: all type of bridges (any construction material)

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- Inspection technologies: the minimum basic instrumentation suggested includes simple measuring instruments to carry out the geometric survey of the structure, photographic instruments with adequate performance for carrying out photographic surveys, even at a distance, and any other instruments considered useful for the survey.
- Inspection procedure: visual inspections shall require the examination of both the extrados and intrados of the bridge in their entirety in order to have a full and adequate view, including, where appropriate, of closed compartments such as caissons or hollow piles.
- Inspection outcome: photographic survey, geometric survey of the main dimensions of the work and survey of the state of preservation of the structure through the compilation of defect forms, which indicate the presence of specific phenomena of degradation and the intensity and extent with which they occur.

In the case of post-tensioned cable-stayed prestressed concrete bridges and bridges in areas with evidence of alluvial, erosional and landslide phenomena, or recognised as being at high hydrogeological risk, with evidence of possible interference with the structure, special inspections must be carried out to verify the need to proceed with the direct execution of in-depth and detailed Level 4 assessments.

- **Level 2:**

The classification of bridges on a territorial scale consists of a simplified and quick estimate of the "risk" factors associated with the structures, surveyed and inspected in the previous levels.

The risk associated with bridges is roughly estimated by means of the Class of Attention (CoA). This Guideline has 5 Classes of Attention:

- High Class
- Medium-High Class
- Medium Class
- Medium-Low Class
- Low Class

The value of the Class of Attention is identified through the simplified assessment of the hazard, exposure and vulnerability associated with the individual work, carried out by processing the results of the visual inspections. Four types of risk are distinguished:

- Structural and foundational risk;
- Seismic risk;
- Landslide risk;
- Hydraulic risk.

It is useful and necessary to analyse the relevant risks separately and independently, defining a classification method and, therefore, a different Class of Attention for each of them, distinguishing:

- Structural and foundational Class of Attention;
- Seismic Class of Attention;
- Landslide Class of Attention;
- Hydraulic Class of Attention.

The methods by which different CoAs are assessed and classified are based on common rules and approaches. The parameters defining them are different and chosen among those considered most relevant for the different types of risks considered.

Once the CoAs associated with the relevant risks are known, they are combined in order to obtain the overall CoA of the bridge, on which to base subsequent actions to be undertaken.

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- **Level 3:**
  Preliminary Level 3 assessments aim at evaluating the quality and type of defects detected at Level 1 (or by periodic inspections) and to estimate, in advance, the resources of the structure according to the project's design standards.

- **Level 4:**
  Consists of a thorough safety assessment.
  In addition to visual inspections that determine the Class of Attention, periodic inspections and special inspections must be carried out when necessary and, in any case, not later than a predetermined period of time. Inspections are combined, when necessary, with non-destructive and semi-destructive testing.

- **Basic inspections:**
  Basic inspections will be carried out at minimum frequencies, according to the scheme in Table 1, depending on the current Class of Attention of the structure:

CoA	Low	Medium-low	Medium	Medium-high	High
Frequency (Structures of “Type 1”)	Biennial	18 months	Annual	Depending on monitoring or semi-annual	Depending on monitoring or semi-annual
Frequency (Structures of “Type 2”)	Annual	9 months	Semi-annual	Depending on monitoring or three-monthly	Depending on monitoring or three-monthly

Table A2. 2 - Class of Attention of the structure

Where:

- Type 1 structures are those already included in a surveillance system compliant with Standard no. 6736/61 / AI of 1967 (of which the state of conservation and the expected evolution of the defects is sufficiently well known).
- Type 2 structures are those, both new or already in operation since several years, for which inspections have not been carried out periodically according to the aforementioned Standard and for which therefore the conservation / maintenance status is not known, as well as the progress of the defects present (real degradation curve).

When conducting basic inspections, the survey sheets must be completed separately for each of the elements defined at the structure level and must be completed with all the indicators represented in the sheets. The inspections shall be carried out visually and with the help of simple tools, such as hammers, length measuring instruments, portable sensors, etc. All defects found must be photographed with adequate resolution and metric references.
In order to assist visual inspections, drones or remotely piloted or robotic vehicles with optics in the visible and infrared range or RGB scanners can be used.

- **Special inspections:**
  The purpose of special inspections is to acquire useful information to deepen the knowledge of deterioration phenomena and the structural condition when basic inspections have found visible criticalities, as well as when exceptional events have occurred, such as major accidents, impacts, earthquakes, floods and landslides that may have affected the stability of the structure and also, in general, when the study of predictive models shows anomalous degradation behaviour, possibly in combination with periodic or continuous

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monitoring systems, such as for the Medium-High and High Attention Classes. In the cases mentioned above, for which the CoA has evolved in a negative sense, special inspections shall be carried out as soon as possible and, in any case, not later than 60 days after the need for them has become known.
In any case, special inspections shall be carried out within 5 years of the previous inspection for items with CoA Low and Medium-Low and within 2 years in other cases.
Special inspections shall be combined with non-destructive testing, including but not limited to the following:

- sampling for mechanical and chemical-physical tests,
- sclerometric tests, sonreb (with calibration cores, as per reference documents) or equivalent,
- pull-out tests,
- ultrasonic or georadar tests for detecting voids and discontinuities,
- electrical potential mapping,
- soundings and endoscope inspections,
- magnetic and/or georadar tests on prestressing cables,
- diffuse moisture and pH measurements,
- Determination of the state of tension.

In addition, for steel structures:

- measurements of the residual thickness of protective paints,
- bolt tightening tests,
- checking welds with ultrasound and/or liquid penetrants.

Special inspections should particularly focus on defects revealed by basic inspections in order to determine their origin, condition and evolutionary trends. The special investigations must be fully documented in a report, with the precise description of the operations carried out, the elements investigated, identified by their code, the results of the tests carried out in situ and in the laboratory, and be accompanied by suitable photographic documentation and the necessary geometric surveys. The report must conclude with an assessment of the state of the work and the evolutionary trends of the deterioration with indications for subsequent actions.
Special inspections may, if deemed appropriate, be accompanied by static load tests and dynamic surveys.

- **Static load tests**

  Before the test is carried out, it is recommended that a careful check be made to ensure that the defects found in the immediately preceding inspection correspond to the current state.
  The test load shall be applied gradually, in successive load/unload cycles, up to the test value and maintained in each load situation for a sufficient time to stabilise the readings of the measuring instruments.
  The application of the loads shall be stopped if deviations from the linear load-displacement behaviour or if lesions, even minimal, appear on the surface of the structural parts or if any other abnormal behaviour is observed.
  Following such events, detailed investigations and safety assessments must be carried out.
  Residual displacements must be less than 5% of the maximum values.
  Measurements of displacement, rotation and deformation must be carried out with appropriate contact or remote instrumentation at significant points of the structure for comparison with the theoretical values and for correct interpretation. It is advisable to include among the physical quantities measured also the temperature of the outside air and in significant parts of the structure, as well as the relative humidity, in order to make the necessary compensations. Where relevant, it is also recommended the measurement of wind speed and direction. The measurement of these quantities and their changes during

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the test must be recorded in the report, together with any other information concerning the environmental conditions under which the test was carried out.

- **Dynamic surveys**
  Dynamic surveys must be conducted in accordance with UNI 10985 "Vibrations on Bridges and Viaducts- Guidelines for dynamic tests and investigations on bridges and viaducts". Detection of dynamic response can be carried out with speed, acceleration, deformation and displacement (rotation) sensors. Applications of laser vibrometry are also possible, while for structures with very large eigen-periods, satellite position sensors (GPS stations) can be used to obtain displacement time histories.
  Experimental dynamic properties are compared with theoretical properties derived from analytical or numerical models, interpreting any differences. Occasional dynamic tests have the primary purpose of allowing the numerical models to be updated, while taking into account the influence of environmental parameters.

- **Structural Health Monitoring (SHM)**
  UNI/TR 11634 are the specific guidelines for SHM, defining:
    - the objectives and design requirements of a monitoring system
    - design criteria for monitoring systems
    - Installation and maintenance of SHM systems

  It also includes principles on:
    - Sensor location optimization algorithms
    - Sensors specifications
    - Data treatment processes
    - FEM model calibration and updating
    - Models for damage identification

A2-2.1.2 Bridges in railways

To maintain the continuous efficiency of the national railway network and ensure maximum safety of circulation and operation, the FSI Group is constantly engaged in the maintenance of the infrastructure and its technological equipment.
A crucial aspect is represented by the control activity, both technical and instrumental, of the infrastructure, also through the aid of mobile diagnostic tools and processes. These activities are governed by procedures and protocols that define the methods of checks, the frequency and the related responsibilities. The diagnostics allows to automatically determine the state of health of the various components of the infrastructure, verifying the degree of wear through an efficient computer system.

The diagnostic systems used are of 2 types:

- fixed: the continuous collection of the characteristic parameters of the infrastructure and the related processing, allow to direct the maintenance strategy towards predictive policies, identifying potential malfunctions to the infrastructure before they occur)
- running (i.e. infrastructure maintenance parameters are systematically checked by means of a fleet of diagnostic trains).

After the transferring, the data, measurements and defects lists are further processed and entered into the Maintenance Information System of the RFI Infrastructure Manager (SIM) known as InRete2000 available to all maintenance operators (each single object is "registered" in the database with appropriate personal data and "classified" on the basis of standard characterizations of the entity; each entity (or groups of homogeneous entities) is associated

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with the relevant maintenance policies and standard work cycles on InRete 2000 through the creation, by the Programming and Control of specific "work orders").

Based on the type of structure and their purpose, maintenance activities are divided into ordinary maintenance and extraordinary maintenance.
Aspects that contribute to the achievement of maintenance objectives:

- specific performance indicators, which represent the reference parameters to ensure the reliability of the different types of systems;
- an efficient information system that allows constant and widespread monitoring of network assets;
- a sophisticated diagnostic activity that allows to verify the different degree of wear of the lines.

Ordinary maintenance activities are aimed at containing the normal deterioration of the infrastructure and are carried out both cyclically, according to scheduled intervals, and to resolve any critical issues.

Extraordinary maintenance activities are planned and carried out for the replacement / renewal of subsystems, or their components, in order to improve their reliability, productivity, efficiency and safety.

Furthermore, in recent years, predictive criteria have been defined to determine, through the historical trend of diagnostic data, maintenance activities and the trend of faults, the most suitable maintenance intervention at the appropriate time, with expected positive effects in terms of optimization of tools, resources and safety.
The maintenance activity is carried out through standardized processes, both in the regulatory part and in the planning part to homogenize the behaviour of maintenance workers throughout the territory, and through the implementation of different maintenance policies:

- **corrective maintenance**: performed following the detection of a failure and aimed at bringing an entity back to the state in which it can perform a required function;
- **preventive maintenance** (cyclical, predictive and according to condition): performed at predetermined intervals or in accordance with prescribed criteria and aimed at reducing the probability of failure or degradation of the operation of an entity;
- **improvement / production maintenance**: improvement / minor modification actions that do not increase the asset value of the entity;
- **extraordinary maintenance**: maintenance undertaken deliberately in order to improve reliability and / or enhance the infrastructure through interventions that increase the asset value.

The FSI Group also ensures the recurring and scheduled maintenance of the road network under concession. During 2019, the inspection of bridges and viaducts also continued through the use of a special application installed on the tablets supplied to the inspectors, which contains all the specialist data of the individual inspected work. This activity, carried out on a quarterly basis, involved over 14,600 structures for a total of 51,000 inspections carried out.

A2-2.2 Needs and challenges

For road bridges, there is a common need to have a clearer specification of the required reduction of traffic loads as a function of the level of risk. The railway sector, on the other hand, follows ad hoc procedures.

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The final objective or expectation is to change from inspections with fixed frequency to interventions conditioned by information deriving from a widespread and continuous monitoring, in order to develop preventive maintenance processes, correlated to predictive models of evolution of damage phenomena. Hence, it is essential to develop a digitalization of this process.

Additionally, there is a need for digitalization of the network and infrastructures, and development of efficient data analysis:

- processes / correlations between data
- identification of outliers
- identification and removal of the influence of environmental effects on the datasets.

The Italian CoP highlights the following key aspects:

- **Type of sensors**: difficult standardization, very much dependent on the structural type and type of phenomenon to be monitored. High dependencies on the technological progress. It is important to set the parameters to be monitored rather than the instrumentation.
- **Accuracy**: to be specified in the design phase of the monitoring system according to the structural type and type of phenomenon to be monitored
- **Data analytics** / engineering of the monitoring approach, with the implementation of a standard technological architecture for data acquisition and data transferring, a digitalized information system and an analysis framework for the interpretation and correlation of data based on AI and advanced Machine Learning techniques.

Furthermore, it has been outlined how the definition of the monitoring system of a new structure is part of the design of the structure itself; in this context, the monitoring system becomes part of the entire design / construction process of a new asset, from the design stages to construction and operation.
The Italian CoP emphasizes that for local authorities, with less technical support, it could be useful to have a general guideline that helps in the choice of the type of monitoring system to be applied according to the structural type and type of prevailing damage, providing the minimum requirements in terms of analysis philosophy and consequent infrastructure management process.

Moreover, it is suggested to classify the structure into Categories. The main idea is to relate Parameters / Key Performance Indicators for the characterization of the phenomena to be monitored for different categories of structures and damage classes.

There is a clear common need raised by the road operators to have more precise indications on the relationship between safety, threshold levels according to the damage scenarios and corresponding maintenance interventions.

In terms of standardization, this should take into account the aspects of digitization (e.g. application of the BIM-Building Information Modelling methodology).

Specifically, standardization is generally valid for non-structural interventions. For structural interventions, the repair measures must be evaluated and customized for each structure.

A2-2.3 Trends

In terms of trends that are outside the standardization, there are not any particular trends regarding inspection, monitoring or technologies that are not mentioned/considered in the

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standards – although it has to be said that none of the standards specify which technology or sensor to use, indeed the attention is on the parameters to be monitored. The general understanding is that in Italy the attention has definitely been shifted towards the installation of monitoring systems after 2018 (collapse of the Polcevera viaduct, sometimes informally referred as Morandi Bridge) and after the publication of the MIT guidelines in 2020. The classification of the existing structures helps the road operators in identifying the structures that require immediate interventions from those that require continuous monitoring and/or regular inspections.

As an example, in Italy Sacertis currently has a network of more than 50 bridges and tunnels under continuous monitoring, using mainly MEMS accelerometers and clinometers, for which diagnostics load tests are undertaken and FE updated models are developed to support the structural identification and the thresholds definition. Automatic alerting systems are set based on the different control parameters and performance indicators. Data have been collected since 2016.

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A2-3 Netherlands

A2-3.1 Current practices

In the Netherlands the public road and rail networks are managed by different governmental bodies.

A2-3.1.1 Current practices: railway infrastructure

ProRail is the Dutch Railway Infraprovider. It has its own specific rules and regulations for asset management, inspection and monitoring, maintenance, etc. These rules and regulations are based on international standards for railways and structures. Because of the specific requirements of railways, where necessary a translation of rules and regulations for railways are made, internationally and nationally.

A2-3.1.2 Current practices: road infrastructure

Rijkswaterstaat (RWS) is the infra provider for highways. Decentral governmental bodies - provinces, municipalities and waterboards - are managing the local network, which of course connects to the highway network. RWS has translated international and national standards where necessary in specific practical RWS standards. Development of processes and knowledge is ongoing, because of the age and changing circumstances of existing structures. The decentral governmental bodies are using their own processes and knowledge causing large differences between the maturity of the asset management process and the knowledge of current condition of the assets.

A2-3.1.3 Current practices: commonly used standards

The ISO 55.000 series about asset management is commonly seen as the standard for asset management. This does not mean that the standard is fully implemented in all organisations, but it is seen as the (future) way of working.

Inspection is related to NEN 2767, which is currently developing towards an international standard. The standard is not fully implemented in all organisations. Inspection companies are aware of this standard and are willing to use the standard.

Due to large differences between expectations in procurement processes for inspection services and accompanying discussions in execution of contracts, problems with interpretation of results etc. an initiative to have a "out of competition discussion" about inspection types, process and results have led to the CUR 117, now CROW-CUR 117. This publication is adopted by governmental bodies, but not fully implemented in all organisations. Inspection companies are in favour of using and continuously improving the standard. For several materials more specific inspection handbooks are written by the working group (e.g. Steel, Concrete, Wood). These publications are describing methods, techniques and non-conformities (also with pictures). Below, details of selected standards are further discussed

- **CROW-CUR 117**
  This publication offers a process and different types of inspection. It is not about inspection technologies, but about the aim of the inspection, the appropriate activities and the kind of results expected. The inspection types in this publication are the following:
    - Routine Inspection (RI)
    - Current condition (CC)
    - Future condition (FC)
    - Further Investigation (FI)

  The standard also describes requirements for inspection personnel, safety, etc.

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Using the publication helps to manage expectations between asset manager and the inspection companies in procurement process and execution.

- **NEN 2767**
  NEN 2767-1+C1:2019 provides an unambiguous methodology to assess the condition of all assets identified in the built environment. A version of this standard will soon be available on EU level: CEN/TC 319/WG 11 'Condition assessment methodologies' NEN 2767-2 provides a summary of the assets that are to be assessed using the condition assessment methodology. The data set containing the assets that are covered by the scope is not restrictive and can be supplemented by the standards committee's request. The standard is focused on buildings, but some is applicable to infrastructure. NEN 2767-1+C1:2019 contains the method to objectively and unambiguously determine and record the condition of building or installation components. The methodology stipulates that the condition assessment shall be recorded objectively, whereby the impact on business operations will not affect the determination of the condition score.

- **NEN 3140**
  NEN 3140+A3:2019 sets out the requirements for the safe operation of electrical installations and of electrical work equipment. It has several paragraphs about inspection of installations and annexes with eg. inspection frequencies, time between inspections, leakage, etc.

- **CROW-CUR 124 safety assessment of existing bridges of decentral governmental bodies (in Dutch)**
  CROW-CUR 124 describes information needed, process and assessment method to be able to assess structural safety of bridges owned by de-central governmental bodies. These bridges differ from highway bridges in use and construction. The document opens the opportunities to prove structural safety according to the Eurocodes and avoid unnecessary disapproval of structures and closure for e.g. heavy vehicles as a consequence.
  Items included: material investigations, alternative load models, advances calculations methods. Content: terms and definitions, assessment framework, assessment process, information and archive, material properties, loads, calculation method.

A2-3.2 Needs and challenges

The variety of structural characteristics poses challenges to standardisation in the context of monitoring. Therefore, the new standard should be open to enable the customisation of the approaches to different cases and applications. However, a standard on monitoring is seen as a mean to support decisions on the reasons why a structure should be monitored and the objectives of monitoring.

It is desirable that the principles and requirements concerning following aspects are considered by the standard on monitoring:

- objectives of monitoring
- choice of suitable monitoring techniques
- additional physical quantities to be measured (e.g. temperature)
- measurement frequency
- sensor layout to reach the prescribed accuracy
- data quality
- data reporting

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Regarding standardisation on the use of monitoring data, guidelines on approaches and requirements for the verification of structural models, determination of load spectra based on monitoring data and the adjustment of partial factors is desirable.

It is foreseen that data management and availability will become relevant topics in the future as a consequence of the increasing number of monitoring projects. In addition the expertise of the data analysis is very important.

Asset managers make use of prediction of future condition to make decisions on interventions (reparation or renovation). Monitoring-driven decision making is not feasible at the moment with the current approach to interventions planning, because handling immediate interventions is complex. Therefore, a bridge management system supported by monitoring is needed.
There is less experience with monitoring on concrete bridges than for steel bridges. Monitoring of concrete bridges is focused on deformation (creep, shrinkage, plastic deformation, settlements, etc.). The most relevant question is: for which failure mechanisms is monitoring useful?

Concerning the use of monitoring data to support the safety assessment, the possibility of reducing partial factors in case that the structural models are calibrated by monitoring data is of interest. The combination of data with predictive models of structural condition is still difficult in practice. Predictions are characterised by large uncertainties and agreements on assumptions and models on project basis should be avoided. Monitoring is often used to control the evolution of the structural behaviour in time. Reliable models are not always available (e.g. for cracking or consequences of settlements), because the cause of such adverse events is not clear and the loads are uncertain. Therefore, it is not always clear what/where/when to monitor.

In addition, the availability of historical data about the structure and the quality of data are key aspects to predict the future condition. Standardisation on this topic is important.

Monitoring projects are customised to the specific case or structure. However, guidelines and requirements could be defined for groups of measurement types and a step-by-step approach to the design of the monitoring system (objectives, what to measure, required accuracy, data analysis, etc.) should be defined in a normative document.

Lastly, there are differences between the smaller municipalities in terms of the use of monitoring. In some of them there are asset managers more interested in exploring and applying new technologies. In others, asset managers rely more on in-depth knowledge of the assets and traditional inspection techniques.

A2-3.3 Trends

- ProRail has experience with monitoring of structural response (e.g. strains), crack growth, settlements. ProRail is developing a monitoring platform for railway bridges with IoT. Inspections remain the most important source of information regarding cracks in fatigue sensitivity structural elements and details (a handbook has been developed).
  Specifically, in the Netherlands, ProRail is using an asset management database called SpoorData, which creates a form of infrastructure passport, ensuring that the asset chain has reliable information about objects. For example, the location of switches, overhead lines and signals, their types, and when they are at the end of their life cycle. It covers both configuration and control data of the infrastructure. Configuration data consists of the (static) object data about 'what is it', 'what can it do' and 'where is it'. Control data (dynamic) includes the maintenance data, failure data and condition data of an object. In 2017, information supply specifications were developed together with the maintenance

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contractors for the nine most important types of objects (including signal, switch and track). These are prioritized on the basis of criteria such as 'performance killers', 'cost drivers' and 'feasibility' and are used to improve the data quality. In 2018, the SpoorData programme will make the data available for everyone in the railway sector to facilitate the exchange of information and data" (GROW, 2019)

- Rijkswaterstaat (RISK inspections) makes use of different methods and tools to gather the information needed for assessing the condition of the structure: "Instandhoudingsadvisering Kunstwerken (IAK) 2020" based on NEN 2767, the RISK (Rijdek Inspecties Stalen Kunstwerken), crack monitoring, deformation measurements, load and response measurements, acoustic emission and ultrasound techniques for crack detection. Monitoring is also used for verification of structural models and calculation of FLS and ULS spectra. It is recognised that monitoring plays an important role in supporting decision making regarding replacement and renovation (e.g. supports of bridges).

- The Rijkswaterstaat has created specifications about how to use the techniques and is developing a qualification of persons instead of a qualification of companies. The integration of monitoring and data at large (e.g. in-car data. IoT) in the management system is an on-going process. In this context, data analysis methods such as artificial intelligence are of interest. Some of the project developments are:
  - crack-PEC technique capable to provide a continuous measurement of a lane in a shorter time.
  - phased array investigation specifically for riding deck. Quality of result are depending on the quality of the person performing the measurements. Specification is ready, qualification requirement in development.
  - sensors (magnetism, acoustic) for crack detection and progress monitoring.
  - Phd research program on load and response measurements.

- First 3D printed steel bridge. A new pedestrian bridge with smart sensors has been built using 3D printing with steel in Amsterdam. Besides the design, the monitoring methods are as well innovative. Autodesk and The Alan Turing Institute have created a Digital Twin to monitor the status in real time including simulation with different condition and loads. Moreover, the municipality can check the traffic flows across the bridge with this monitored data. In Amsterdam city, monitoring is used more and more in combination with inspections to support preventive maintenance and budget planning. Monitoring plays a role also for safety assessment (program on bridges and quay walls, where info from inspections, monitoring and safety assessment are combined for risk assessment).

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A2-4 Poland

A2-4.1 Current practices

The current Polish design regulations do not define any requirement regarding structural monitoring systems to be installed as part of newly built road engineering facilities. Nevertheless, in case of more important structures, there is a load test obligatory before handing over for use.

Obligation of inspection of bridges, viaducts and other road engineering facilities is required in Poland by building regulations i.e. article 62 of the Construction Law (Prawo Budowlane - Dz. U. 2020 r. poz. 1333). Duty of control is imposed on infrastructure owners or administrators.

Basic inspection of an engineering facility is performed at least once a year. The purpose of such inspection is to assess and record the current technical condition of the entire facility, as well as to determine the conditions of safe operation, as well as the needs and scope of necessary maintenance works, including repair works.

Extended inspection, is done at least every five years, are performed similarly to basic inspections, but they should take into account the comprehensive technical condition of the structure, including the condition of the load-bearing elements. In addition, it is necessary to assess whether the load capacity of the structure is maintained in order to introduce tonnage restrictions or restrain the traffic until a comprehensive renovation or rebuilt of the structure is carried out. The conditions of safe operation of the facility for the next five years of its use, have to be determined as well.

An owner or administrator is obliged to keep “the object book” with up-to-date and full documentation of its technical properties. Required detailed contents and templates of an object book are defined by relevant ordinance (Rozporządzenie Ministra Infrastruktury z 16 lutego 2005 r. w sprawie sposobu numeracji i ewidencji dróg publicznych, obiektów mostowych, tuneli, przepustów i promów oraz rejestru numerów nadanych drogom, obiektom mostowym i tunelom – Dz.U. 2005 nr 67 poz. 582; eng.: Ordinance of the Minister of Infrastructure of February 16, 2005, on the method of numbering and recording public roads, bridges, tunnels, culverts and ferries and the register of numbers assigned to roads, bridges and tunnels).

A common good practice standard is set in Instructions for conducting inspections of road engineering facilities prepared by General Directorate for National Roads and Motorways (Instrukcje Przeprowadzania Przeglądów Drogowych Obiektów Inżynierskich, stanowiące załącznik do zarządzenia nr 35 Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 28 września 2020 r.; eng.: Guidelines for conducting inspections of road engineering facilities, attached to the order no. 35 of the General Director for National Roads and Motorways).

Both types of inspections include visual inspection as well as essential tests and measurements.

Activities of basic inspections are preformed from deck level or surroundings of the facility with use of binoculars, ladders or scaffolding. In case of extended inspections, activities are also performed in approx. distance of 1 m allowing recognition of any defects with bare eye, hence use of scaffolding and other devices is usually necessary.

Essential tests and measurements executed during inspections consist of:

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- tapping with 0.5 kg hammer,
- tearing off fragments of corroded layers,
- drilling selected fragments of timber structure with 5 mm drill,
- measurement of cracks,
- measurement of defects with measuring equipment.

During extended inspections photographic documentation of the facility and its damages has to be created.

Both types of inspections (basic or extended) should be carried out by a professional with building licence in the relevant specialization, belonging to a chamber of civil engineers during the inspection and holding an appropriate certificate issued by the chamber and trained in the performance of inspections.

A2-4.2 Needs and challenges

The scope and detail of inspections and monitoring carried out as part of the maintenance of road engineering facilities directly depend on the funds allocated for these purposes. In this sense, the challenge for the coming years is to ensure adequate budgets to handle the increasingly extensive and aging infrastructure.

The subject of road tunnels inspections and monitoring in Poland is little known due to the existing insignificant number of such infrastructure facilities. Nowadays, several road tunnels are under construction, and some of them are large facilities, so it will be a challenge for the future to establish national practices for their regular inspection and monitoring.

Various types of road engineering facilities may require installation of individually designed monitoring systems. It results directly from the uniqueness of structures of infrastructure facilities. However, it is possible to adopt a single standard that enables collection, archiving and analysis of the measurement data. There is currently no single dominant standard. There is no national draft on guidelines for the processing of structural monitoring data.

A2-4.3 Trends

Over the past 20 years, more than a dozen bridges in Poland have been equipped with monitoring systems. It should be noted that in this initial phase of application of this type of solutions, mostly newly-built outstanding objects were selected – with above-average dimensions or being innovative structures. The monitoring of structures also applied to couple of facilities located in the areas of mining damage in order to assess their suitability for further use. Among the monitored objects there are none of the oldest ones built more than 50 years ago.
For example, in the case of the Rędziński Bridge, the large span and non-standard structure of its pylon (the highest pylon in Poland - 122 m) triggered the designer to propose a monitoring system for this bridge. Similarly, in the case of the bridge in Puławy, the large span and the structure of the bridge main span (the longest arch span in Poland - 212 m), especially liable to thermal influences, prompted the investor to implement a bridge monitoring system.
The first Polish road bridge made of FRP composites, in Błażowa, was also equipped with structural health monitoring because of its high innovation and necessity to better understand the long-term behaviour of the beams made of the new material.

For measurements, mainly string sensors and fiber optic sensors are used, and commonly measured values are:

- forces in tendons,
- angular displacements,

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- linear displacements,
- deformations,
- accelerations.

The measuring technique DFOS (Distributed Fibre Optic Sensing) is also used in Poland. Fiber optic were installed on such bridges as:

- steel suspension “Brama Przemyska” bridge in Przemyśl,
- steel suspension Tadeusz Mazowiecki bridge in Rzeszów,
- composite beam bridge in Nowa Wieś,
- footbridge in Nowy Sącz.

One of the examples where the DFOS technique was used is the construction of a footbridge in Nowy Sącz. It was created as part of the European EuroVelo cycle route network project. The footbridge has a span of 78 meters and a usable width of 2.5 meters. The supporting structure of the footbridge consists of two steel arches with a tubular cross-section Φ508 mm, symmetrically inclined towards the inside of the structure. The platform is designed as a closed cross-section with a hybrid concrete-composite structure. Additionally, composite reinforcement based on FRP composite was used (including EpsilonRebar fiber optic sensors). It was concreted in a continuous manner over the entire span of the span.

There are also sensors, i.e. Weight In Motion, which enable the detection of vehicles with excessive weights, and provide information about the volume and structure of traffic on the site.

Often, the monitoring of structures is accompanied by meteorological monitoring.

Usually, data from sensors in the facility are collected and pre-processed by a local server and then sent to centres where, after further processing, they are available to the staff responsible of infrastructure maintenance.

In summary, structural health monitoring is not a commonly used solution in Poland. Selected facilities have been monitored on the basis of individual decisions of their investors or managers. In each of these cases, the requirements for functionality, accuracy and data formats were formulated by the ordering parties in relation to the particular projects.

The developments of SHM technology are driven by the activities of specialized companies that commercially deal with implementation of structural health monitoring systems and by research organizations cooperating with them. Further directions of development focus, among others, on introduction of algorithms based on statistics and the calculus of probability; development of intelligent decision algorithms; implementation of FEM model in monitoring system.

Recent years have shown the need for newer and innovative technologies. One of such novelties is bridge digital twin. In the case of the bridge, their digital models are built so that the results of the inspection can be directly placed on the bridge model. Conservators or bridge inspectors have an appropriate application on a smartphone/tablet that support them during their work. During the inspection, the bridge models are displayed on the screen to determine direct damage. This allows to understand the processes during the use of a real facility, predict events, effective remote management, early detection of failures and monitoring of component wear. Other devices that can support the inspection of engineering facilities are drones equipped with a camera on the device's forehead and mixed reality glasses.

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A2-5 Nordic countries : Norway, Sweden, Denmark, Finland and Iceland

A common description for the current practices, needs, challenges and trends are given for all Nordic countries, as common cultural, geographical and language influences may generate similar practices. The Community-of-Practice-meetings were organized as one joint meeting for all the Nordic countries Norway, Sweden, Denmark, Finland and Iceland. When country specific information is given, it is stated explicitly.

A2-5.1 Current practices

The standards and current practices in maintenance, monitoring and inspections of bridges and tunnels in the Nordic countries have a lot in common. At national level, governmental objectives are set, typically aiming for safe, sustainable and economical transport systems throughout their service life. Transport authorities issue standards that regulate the responsibilities of the actors and give specific directives for certain procedures. Parts of the management process are often outsourced.

For bridges and tunnels, inspections are carried out to ensure structural safety. Inspections are regulated in a similar way in all Nordic countries. There are different levels of detail described in the standards, where simple inspections are done more often and detailed inspections more seldom. Visual inspection is the dominating method, whereas extended investigations with non-destructive and destructive measurements are used for objects with higher concern. Most inspections are time-based at a regular interval of one to six years. Condition-based intervals for inspections are acknowledged by a few of the Nordic standards. Quantification of damage is treated extensively. The scale for most inspection data is ordinal, meaning that damages are ranked qualitatively on an arbitrary scale, usually with three to five classes. Consequences are identified categorical and/or are ranked on a similar scale. A simple measure of risk may be outlined for prioritizing among structures. For some damages, more details on damage quantification is given, e.g. measurement of crack width and length. The link between observed quantities and the structural capacity is weak. Typically, Eurocodes for design of new structures make the basis for assessment of existing ones, often adjusted with modified partial safety factors. There is little guidance on accounting for damages and prediction into the future.

The information management systems organizing the structure specific information are recognized as important for efficient maintenance. The level of standardization of these aspects is spread. Automized data collection, process and storage aligned with the concept of a digital twin is not treated. Monitoring, reliability assessment and full-scale load testing are methods that are not yet well standardized and only adopted rarely.

The introduction given shows that inspection procedures are rigorously described in standards within the Nordic countries, but the connection between inspections and structural safety is limited. For monitoring, standards are not well established. In the following, country specific standards are presented.

A2-5.1.1 Current practices : road bridges in Norway

The safety of national road bridges is the responsibility of the Norwegian public roads administration (Statens Vegvesen). The regulation R411 Bruforvaltning riksveg (Bridge management national roads) (Statens Vegvesens, 2018) outlines the basis for management of bridges and other load bearing structures along national roads. This regulation aims to assure that the public demands of unified safe and functioning load carrying structures in the national road network are fulfilled. It states that the bridge owner should appoint a bridge

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manager that is responsible for the tasks outlined in this standard. The regulation refers to the guideline V441 Bruinspeksjon (Bridge inspection) (Norwegian public roads administration, 2019) where additional requirements are set.

- **Bridge management system**
  - Scope: Load bearing structures in national road network
  - Periodicity: Continuously
  - Methodology: Registration of data in a designated bridge management system from planning of bridge until bridge is taken out of service. Assessment of the load bearing capacity of existing structures when needed and follow-up of measures in the event of change in load bearing capacity. Mapping, evaluation, communication and mitigation of risks.

- **Inspections, general**
  - Scope: Load bearing structures in national road network
  - Periodicity: Regularly
  - Methodology: Bridge inspections should be carried out regularly and results should be reported in the bridge management system as soon as possible and at latest the same year as inspection was performed. The registered information should undergo quality control and be followed up by appropriate actions. Assuring competence and experience of inspection personnel is the responsibility of the bridge manager. Each bridge must have an updated inspection plan.

- **Inspections, damage assessment**
  - Type of damage: The type of damage is classified in main categories such as general damage, ground damage, concrete damage, steel damage, etc. Each main category has subcategories.
  - Degree of damage: The damage is quantified by the following gradation (further guidance to be find in appendix to the bridge inspection handbook)
    - 1. Small damage
    - 2. Medium damage
    - 3. Large damage
    - 4. Very large damage
  - Consequence type of damage: The consequence is described by consequence type and degree of consequence. One damage can have several types of consequences, denoted by the following letters.
    - B Structural integrity
    - T traffic safety
    - V maintenance cost
    - M environment/appearance
  - Consequence rating of damage: In the type of consequence, an indication of the importance of the consequence is given, where B is the most severe consequence and M is least severe. In addition to this, a rating of the consequence is done as follows.
    - 1. Low. No action required.
    - 2. Moderate. Consider reporting possible actions in bridge management system.
    - 3. Considerable. Report possible actions, reassess inspection interval.
    - 4. Contact bridge manager immediately.
  - Priority of damage: A priority is calculated by multiplying the degree of damage by the consequence of damage, resulting in a risk matrix with priority 1-16.
  - Cause of damage: The cause of damage should be given when possible for main inspection and special inspection. Selection of causes:
    - Design error

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        - Lack of maintenance
        - Environmental attack
        - Environmental loading
    - Progress of damage: This is acknowledged as an important aspect but no guidance is given.

- **Simple inspection**
    - Scope: Load bearing structures in national road network
    - Periodicity: Default period 1 year, except from the year when main inspection is carried out. Simple inspections may have a longer interval or be cancelled until next main inspection if a risk and vulnerability analysis approves that.
    - Inspection technology: Visual inspection of the main elements visible without lift, boat, drone or other special equipment. Binocular should be used when needed.
    - Inspection procedure: The structure is inspected for damages and other circumstances that could have impact on the structural safety or performance. At least damages that are evaluated to require action before the next simple or main inspection should be registered in the bridge management system.
    - Inspection outcome: Registered information in bridge management system and appropriate follow-up.

- **Main inspection**
    - Scope: Load bearing structures in national road network
    - Periodicity: 3 years for quays and moveable bridges, 5 years for other structures. After a risk and vulnerability analysis, the inspection interval can be extended to maximum 10 years.
    - Inspection technology: Visual inspection of all structural elements and other inspection technologies if needed. Technologies are further described in appendix V2 Methods measurements/material investigations, which refers to R210 Laboratory investigations and R211 Field investigations. The following technologies are treated:
        - General measurements: Geometric levelling, measurement of displacements, pavement thickness and pavement rutting
        - Inspection technologies for concrete: concrete cover, reinforcement location, crack width, carbonatisation depth, chloride content, corrosion potential, concrete strength, aggregate properties
        - Inspection technologies for prestress tendons: including ultrasonic testing, impulse response, impact echo, thermo-camera and removal of concrete to expose tendons for visual inspection
        - Inspection technologies for steel: radiographic testing, bolt and nail testing, ultrasonic testing, penetrant testing, eddy-current testing, magnetic particle testing, fiber-optics
        - Inspection technologies for timber: radiographic testing
    - Inspection procedure: The structure is inspected for damages and other circumstances that could have impact on the structural safety or performance. The bridge inspector should have engineering background and knowledge about degradation mechanisms and structural functionality of the bridge type to be inspected.
    - Inspection outcome: Registered information in bridge management system and appropriate follow-up.

- **Special inspection**
    - Scope: Extraordinary event or need for further investigations.
    - Periodicity: None
    - Inspection technology: As needed.

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- Inspection procedure: Object specific. In general, it includes detailed investigation and identification of mitigation alternatives including cost estimates.
- Inspection outcome: Report and appropriate follow-up.

A2-5.1.2 Current practices : road and railway bridges in Sweden

The main authority responsible for both road and railway infrastructure is the Swedish transport administration (Trafikverket). Requirements are set in the document Inspektion av bro och övriga byggnadsverk (Inspection of bridge and other structures) (Swedish transport administration, 2020). It aims to describe requirements on the infrastructure properties and on operation and maintenance.

- **Inspections and damage assessment, general**
  - Scope: Bridge, ferry berth, quay, trough, pile deck, retaining wall, device for maritime traffic, snow gallery, noise protection screen along railway
  - Periodicity: Depending on type of inspection
  - Methodology: Structures should be inspected regularly and systematically. They should be assessed compared to the condition as built. The functional condition should be specified as condition class 0-3. Damage investigation should be carried out for structures with condition class 3, and otherwise when needed. Special inspections are also done on demand. Emergency deficiencies identified at inspections that may impair traffic safety or structural safety should be reported immediately.
  - Inspection outcome: Damages should be reported in the bridge management system BaTMan within 10 workdays. The following should be reported for damages:
    - Description of damage
    - Physical condition, measured with relevant methods if applicable
    - Functional condition
    - Possible repair, including cost estimate
    - Location
    - Photo describing extent, type and location of damage

    Special inspection or damage investigation should be scheduled depending on the condition classes assigned.

- **Main inspections**
  - Scope: All construction elements that influence the structure's performance or safety, including inside of structure.
  - Periodicity: Depending on the condition of the structure, at least every 6 year.
  - Inspection technologies: To such extent that the physical and functional condition can be assessed.
  - Methodology: Bridge inspections should be carried out at arm's length in daylight. Visual inspection methods that are as accurate as arm's length inspection can be used. Binocular is not permitted. Measurement and documentation of the following should always be done:
    - For corrugate steel bridges, loss of steel due to corrosion
    - Bearing position for moveable bearings
    - Moisture content and temperature in closed areas with fixed measurement equipment
    - Moisture content in timber bridges at lower side.

    It should be evaluated whether complementary special inspection is needed, including underwater inspection. Specific competence requirements are set for bridge inspectors.
  - Inspection outcome: Condition class assessments

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- **Special inspections**
  - Scope: Construction elements or damages that require in depth assessment, special competence and/or follow-up between main inspections.
  - Inspection technologies: As needed.
  - Inspection procedure: Depending on aim of special inspection. Examples are assessment of:
    - Sea bed profile
    - Reinforcement corrosion
    - Chloride content and carbonatisation in concrete
    - Bolts and rivets
    - Welds
    - Waterproof membrane
    - Moisture content in timber structures
  - Inspection outcome: Depending on aim of inspection.

- **Damage investigation**
  - Scope: Type of special inspection to determine the influence of a condition on the structural safety or traffic safety. Should be done for structural elements with load bearing or traffic safety functionality that have been assigned condition class 3 at inspection.
  - Inspection technologies: No guidance
  - Inspection procedure: No guidance
  - Inspection outcome: No guidance

A2-5.1.3 Current practices : road and railway tunnels in Sweden)

Requirements for tunnels in the document Inspektion av tunnel och bergkonstruktioner (Inspection of tunnel and rock constructions) (Swedish transport administration, 2020) follows the same procedure as for bridges. A few exceptions are described here.

- **Specific requirements for tunnels:**
  - For main inspection of tunnels, the following should always be done:
    - Measurement and documentation of air temperature
    - Mapping of leakage and presence of ice
    - Physical assessment of shotcrete delamination from rock by hammering
    - Physical assessment of loss of rock stress by hammering
  - Required competence is related to geotechnics
  - Special inspections include special inspection of water and ice and special inspection of rock slopes.
  - Special inspection of rock slopes

A2-5.1.4 Current practices (road and railway bridges in Denmark)

The handbook Eftersyn af bygværker (Inspection of structures) (Vejregler, 2019) aims to unify inspections of the condition of structures.

- **Inspections, general**
  - Scope: Structures in the traffic network including bridges, pile decks, retailing walls, service tunnels, pipe culverts, stone box culvert and gates.
  - Competence requirements: Qualifications are defined for each type of inspection. For principal inspection, a specific course must be taken.

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- **Routine inspection**
  - Scope: Ensure the functionality of structures and safety of the road network. Conditions affecting road safety, the environment and/or economy should be reported, to support maintenance planning.
  - Periodicity: Decided depending on the traffic and type of structure, age and condition. Typically once a year.
  - Inspection technology: Not applicable.
  - Inspection procedure: Visual inspection of the accessible parts of the structure. Identification of damages and inspection of water and winter conditions.
  - Inspection outcome: Report of damage and need for maintenance work.

- **Principal inspection**
  - Scope: Provide a basis for initiating activities to ensure long term safety of traffic network and preservation of the value invested in infrastructure.
  - Periodicity: Regular intervals of 3-6 years depending on the condition. 1 year if the condition is very bad.
  - Inspection technology: Mainly visual inspection, possibly simple measurements with hand-held tools.
  - Inspection procedure: Assessment of damage, cause of damage, condition grade for each structural element and the structure as whole, evaluation of need for special inspection or maintenance works. The condition grade is determined according to a special point system that results in a total condition grade at scale 0-5.
  - Inspection outcome: Results in a report.

- **Special inspection**
  - Scope: Providing the infrastructure manager with more accurate support for decisions on prioritization of maintenance activities, than achieved by principal inspections.
  - Periodicity: None.
  - Inspection technology: Non-destructive and destructive tests, laboratory test of material samples, as required by the specific situation.
  - Inspection procedure: Technical special inspection includes determination of extent and cause of damage. It may include periodic measurements and/or an assessment of the load-carrying capacity. A financial special inspection is a financial analysis that investigates different repair strategies and their economic effects.
  - Inspection outcome: A basis for decisions on maintenance planning.

A2-5.1.5 Current practices (bridges and tunnels in Finland)

In Finland The Finnish Transport Infrastructure Agency (FTIA) is the responsible administration to make standards, as guidelines and quality requirements, for engineering structures as bridges and tunnels. FTIA owns also Taitorakennerekisteri, the Asset Management System for Engineering Structures. Municipalities, as cities, can use the asset management system but they are free to use own systems or make own guidelines. All standardization is written in Finnish.

In the inspection system for engineering structures the used inspection types are yearly inspections, general inspections, widened general inspections (for larger bridges) and special inspections. Three first inspection types are normally time-based. Special inspections are as standard made for structures before larger reparations. For critical bridges or bridges in end-use inspections can be made as condition-based also.
Inspection types, methods, damage classification and the quality requirements are described in different level guidelines: generally in The Inspection Guidelines for Engineering Structures,

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specifically in manuals for different structure types and in quality requirements for different inspection types.

The general inspection, usually made every fifth year, is the main inspection type made by specialists having the inspector examination for certain engineering structures. Using the manuals damages are classified to classes 1…4, condition estimates are given for main structural parts and the whole structure and the need and urgency of further actions are given and put into the management system.
The Asset Management System of Engineering Structures (Taitorakennerekisteri) is the main database for all information of engineering structures from design stage to use and maintenance. Data for single structures (as single bridges) is containing basic data, design and inspection documents, load-carrying capacity data, photos, condition data with inspection documents, information from carried out and planned actions etc. The system is also calculating some special indexes for condition, as the repair need index (KT), and can be used as programming tool for repair actions for the set of structures. Some damage prediction models have been in test use before but they are not integrated to the current management system.

FTIA has made instructions for load bearing capacity calculations in the Guideline for load bearing capacity calculations. Calculations allow lower safety levels than in design of new structures. Material properties and parameters are mainly the same as in the Eurocodes. The greatest difference lies in the safety factors, which depend on the degree of exactness of the bridge data. The lowest factors can be used if all critical dimensions of the structure have been measured and the material strengths have been ensured. If the structure is damaged, all damages have to be taken into account if they affect the bridge capacity. Damages are considered in terms of capacity and stiffness of the structure in the FEM-model. If there is a need for more accurate calculations, load tests may be used to get as accurate data from the structural behaviour to FEM-model as possible.

To give guidance and quality requirements for bridge repairs three levels of SILKO-manuals, as for different bridge main materials are given: general guidelines, manuals for different repairing methods and acceptance qualification and classifying for materials. There are also guidelines for strengthening and widening of concrete bridges.

A2-5.1.6 Current practices (bridges and tunnels in Iceland)

No relevant standards are available in Iceland.

A2-5.2 Needs and Challenges

In general terms the needs are focused on the necessity for following damages in time and space and an asset management system. Nevertheless, each country has detected specific needs based on its previous experiences and challenges. In the following paragraphs, a description of the needs and challenges will be explained based on the CoP meetings executed during the IM-SAFE project.

A2-5.2.1 Needs and Challenges in Norway

- **Trøndelag fylkeskommune (county counsil):**
  - In general, the main concern is the growing backlog of bridges that needs corrective maintenance. Maintenance budgets for 2019 and 2020 were decent, but for 2021 there is a significant reduction in the budget. If this trend continues, restrictions in traffic load will have to be imposed for the most damaged bridges, and this will result in negative economic effects to the regions industry that rely on transporting goods.

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- Grouting of bridge post-tensioning tendon ducts: In the autumn of 2019, the Norwegian Public Roads Administration started maintenance work on Herøysund bridge in Nordland county. During removal of concrete to install cathodic protection delamination of the concrete around the tendons was discovered. Further inspections found that the grouting of the tendon ducts had been improperly injected during construction. This had left the tendons susceptible to corrosion, and many were found severely corroded. Trøndelag County Council worries that there could be similar problems in other similar bridges. It is required to find a suitable non-destructive test that can check for air pockets around the tendons.
- Alkali-silica reaction issues were raised in general.
- Improved asset management of large coastal bridges: Trøndelag County Council has 38 coastal bridges built before 1990 that are more than 100 meters long. Getting accurate information from monitoring and inspection of these bridges is crucial as the economic gains from preventive and well planned maintenance are considered to be substantial.

- **Railways BaneNor**
  - Assessment procedures are not specific enough and that is producing issues when hiring consultants/contractors. The lack of specifications is especially concerning in tunnels.
  - In relation to tunnels, lining for water and frost protection is key, while when discussing about bridges it is agreed that many old bridges in steel suffer from corrosion.

- **Innlandet fylkeskommune (county counsil):**
  - There are a total of 1233 bridges/ constructions, with some of them approaching the end of their service life. The maintenance needs are high. Railing, concrete damage and collision damage are being the main issues that are being faced in Norway.

A2-5.2.2 Needs and Challenges in Iceland

In Iceland, there are a few older tunnels do not comply with the latest tunnel safety regulations and need upgrading. The bridges in that country are between 40-50 years old.

One of the main issues is that not many engineers/specialists work on maintenance or inspections and they foresee an increased demand in the coming years. Unfortunately, it is perceived that in universities, there is very little focus on the performance of structures, universities are mainly focused on new structures.

A2-5.2.3 Needs and Challenges in Finland

The FTIA (Finish transport infrastructure agency) highlights that a more systematic method for assessment in order to be more efficient when decision making in future is needed.

A2-5.2.4 Needs and Challenges in Sweden

One of the main concerns in Sweden is related to the recent introduction in the country of heavier vehicles (74 ton) which requires a lot of strengthening work.

A2-5.3 Trends

A2-5.3.1 Trends in Norway

- **Trøndelag fylkeskommune**
  - **Condition based inspection programme:** Previously, bridge inspections were time-based. In 2017 the regulatory agency provided a guide for using a risk and vulnerability analysis (Norwegian: ROS-analyse) in order to change the inspection intervals

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resulting in a shift from strictly time-based inspection routine to a more condition-based inspection programme. In short, the bridges are divided into groups of similar type and external conditions. For each analysis, damages, degradations, traffic load and registered vulnerabilities of the individual bridges are evaluated. Based on the overall assessment of each bridge we decide if it needs annual inspections, or if it is deemed safe to monitor the bridge at longer time-intervals.

- **Drone inspection**: A cooperation started in 2018 with certificated drone pilots performing test inspections on a selection the bridges. The first full scale drone bridge inspection was done in February 2019 when Elgeseter bridge in Trondheim was inspected using two drones. The inspection was carried out without any disturbance to the traffic.
- **Sensor monitoring:** Monitoring traffic loads and condition of bridges using sensory equipment is very new to Norway. In 2020, a pilot project started in cooperation with a company named Ferrx where we retrofitted two steel bridges with patented FEMM sensors (Ferrx ElectroMagnetic Method). FEMM measures the stresses caused by the traffic loads inclusive stress due to any mechanical resonance. Furthermore, it monitors the effect these loads have on the monitored steel, e.g. changes of residual stresses in welds and material degradation that can lead to crack initiation and growth.
- **Cathodic protection:** Cathodic protection (CP) is used to prevent corrosion of reinforcement in concrete, mainly caused by chloride contamination. The corrosion is prevented by making the reinforcement function as a unified cathode by mounting an external anode on/in the concrete and applying a direct voltage between the electrodes. In Trøndelag County there are five bridges where cathodic protection has been used for retrofitting. Two of the cathodic protection systems are old, dating back to 1993, and are at the end of their expected lifetime. The other three were installed between 2012 and 2017. In addition to protecting the reinforcement, the CP-systems provide valuable information through performance assessment tests. By cutting the electric current and measuring the 24-hour decay potential, the degree of protection of the reinforcement is indicated.
- Reliability**-centered maintenance (RCM):** Since the maintenance backlog is so long, very little preventive maintenance is done on the bridges. One exception is two movable bridges Nidelv bru and Jernbanebrua. It is of high importance that these two bascule bridges function reliably, so there is a cooperation with the consultant firm MainTech in making an RCM-analysis for both bridges. The RCM reports were finished by the end of 2019, and so the system is still in the early stages of implementing the new maintenance schedule on both bridges. The maintenance personnel is currently learning how to use the report and follow the new schedule for preventive maintenance. It is still early to draw any conclusions on the long-term effects on reliability and maintenance costs of the two bridges, but the current results are promising.

A2-5.3.2 Trends in Finland

- **Finland Väylävirasto Finnish Transport Infrastructure Agency (FTIA)**
  Bridge loading tests have been a tool to study the real behaviour of the bridge for load bearing capacity assessment, quite much used from 1980's. Bridge health monitoring using short-term and permanent monitoring systems has become a new tool to define also real bridge loadings, bridge condition development and the effect of it as also the environmental effects, etc. For guidelines and quality requirements of loading tests and health monitoring of bridges two documents are written: Bridge monitoring guideline (to define the processes and procurement) and Bridge monitoring handbook (to present the different methods, measuring techniques, data management, design process, etc.).

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Basic information from new bridges can be brought to the asset management system from BIM-models, which in IFC-format can be saved to the system also for the use during maintenance stage. BIM models can be made also for larger repairing actions. For BIM-modelling requirements of bridges there is a guideline BIM Guidelines for Bridges, which will be updated in the near future.

A2-5.3.3 Trends in Sweden

- **Swedish transport administration**
  They use BIM for new bridges (and plan to do it for some of the existing in the future).

A2-5.3.4 Trends in Denmark

- **Danish Road Disrectorate**
  Aiming for risk based predictive maintenance, the Danish road directorate are implementing dTIMS (a data management system) arguing that a good asset management system is essential for effective maintenance. The dTIMS platform is an enterprise asset management solution that encompasses strategic planning with maintenance operations and capital investment decision making.
  With more objective condition data, e.g. by automatedly collected data, transparent decisions can be made. This new system will allow for e.g.:
  - automated measurements of pavement conditions with advanced vehicles
  - lasers scanning the road shoulders
  - drone inspection of bridges
  - integration of sensors into structures
  - “Big data” analysis

  At first, bridges/structures and pavements will be implemented in the dTIMS system which is planned to be taken in operation in mid-2023.

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A2-6 Spain

A2-6.1 Current Practices

A2-6.1.1 Current Practices: bridges in railways

In Spain, the conservation of railway infrastructures is a basic need, both for the safety of railway traffic, and for the maintenance of an adequate level of service during its useful life. Railway bridges are key elements of the railway infrastructure, therefore their maintenance and conservation demand special attention. This requires carrying out periodic technical inspections, as well as, where appropriate, the pertinent repairs, with two aims: avoiding risks that may cause accidents and keeping the bridges in an adequate condition of use, minimizing the conservation costs associated.

The former Ministry of Development, called today Ministry of Transport, Mobility and Urban Agenda (MITMA), published in 2005 a standard for railway bridges inspection (ITPF-05). This standard was published to update the previous standard from 1975 which stablished the obligation to carry out inspections and load tests on new construction railway bridges. Since this standard aimed at studying only new construction bridges, the 2005 standard updated its content in relation to inspections and load tests, developing them with greater detail and giving them greater relevance, not only for the verification of the correct execution of new bridges, but also for the bridge management throughout their life cycle. Besides, the standard appoints the creation of a register (record book) of inspections of railway bridges, in which the information related to the inspections, tests and repair actions to which they have been subjected has to be recorded. Each railway infrastructure administrator in Spain must comply with the provisions of this standard.

The standard ITPF-05 “Guideline for railway bridges technical inspections” comprises the following key aspects:

- **Main inspections**
  The purpose of the main inspections is to obtain information on the functional and resistant state of a bridge at a given time, in order to verify that it is capable of fulfilling the function for which it has been built, with an acceptable level of safety.
  - Scope: all bridges with a 6 m span or above (any construction material)
  - Periodicity: every 15 years maximum
  - Inspection technologies: not specified, only visual inspection is required
  - Inspection procedure: each main inspection will consist of a planned and thorough examination of all elements of the bridge. Fundamentally, the state of the structure will be checked, analyzing the damage or existing deterioration and its evolution since the last inspection carried out. All available documentation related to the bridge will be used; if applicable: construction project, incidents that occurred during its life, reports of previous inspections, etc. The aspects to be covered during the inspection are:
    - General condition of the visible parts of the foundations and the support ground
    - General condition of the substructure (abutments and piles).
    - General condition of the superstructure: load-bearing elements, deck, etc.
    - General condition of the auxiliary elements: support elements, expansion joints and deck drainage system.
    - General state of the accesses to the structure.
  - Inspection outcome: Report (standard form)
    - Damages classification:

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- Class 1: the damage can affect the safety of the structure and, therefore, its ability to withstand the loads for which it was designed. The report should include a damage assessment, repair works times (max. 4 years) and operation restrictions, if required.
- Class 2: the damage can affect the life cycle of the structure (long-term structural safety).

- **Special inspections**
  When after the main inspection of a bridge it is necessary to gather additional information, and as a preliminary step to correcting the deficiencies, a special inspection may be carried out. This inspection may include the execution of complementary tests, the complete analytical check of the structure and even carrying out load tests.

- **Basic inspections**
  The purpose of the basic inspections is to monitor the general condition of the bridge almost permanently, allowing to detect as soon as possible, and without waiting for the next scheduled main inspection, the appearance of any real or apparent damage susceptible to follow-up or repair.
  - Scope: all bridges with a 10 m span or above (any construction material)
  - Periodicity: every year
  - Inspection technologies: not specified, only visual inspection is required
  - Inspection procedure: visual inspection of the elements of the bridge.
  - Inspection outcome: report describing minutiae and standard form if major damages are found. The outcome of the inspection might be also the need to perform a main inspection.

- **Load tests**
  The purpose of load tests in bridges in operation is to increase knowledge of the state of the structure by evaluating its structural behaviour, either periodically or as a result of the inspections. The displacements and deformations in certain relevant elements of the bridge will be measured, under the action of the test loads, comparing them with those obtained in previous tests.
  - Scope: all steel or steel and concrete bridges with a 10 m span or above.
  - Periodicity: every 15 years maximum for bolted joints bridges and every 30 years maximum for welded joints bridges.
  - Technologies: not specified.
  - Inspection procedure: particular for each bridge.
  - Inspection outcome: Report and standard form.

- **Railway Bridge Inspection Record**
  The aim of the standard is also to provide a guideline on how to gather the results of the inspections and tests.

Moreover, based on the standard ITPF-05 (Spanish Ministry of Transport, 2005), ADIF, the Spanish state-owned railway infrastructure manager under the responsibility of the Ministry of Transport, Mobility and Urban Agenda (MITMA), has its specific standards for inspecting bridges in railways that provide more details on the above stated:

- **Main inspections (ADIF's standard: Main inspection of railway bridges, NAP 2-4-0.1)**
  The standard gathers in more detail the methodology to follow when inspecting a bridge and the way the information will be gathered and processed. Regarding the methodology, the document includes a catalogue with all the main assets to be inspected and the standard way to name them, a definition of each of each of the assets, the usual damages,

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and the criteria to define a damage intensity level, a guideline on the itinerary of the inspection, and the methodology to categories the damages and the level of importance of the damage, which depends on the type of damage, the affected asset and the level of intensity. There are 4 level of importance of the damage, which correspond to the two classes of damage defined in ITPF-05.

All the information collected by the inspector will be uploaded to ADIF's systems for its processing and the definition of the following 4 indexes:

- Status of the structural elements.
- Foundation condition.
- Status of the non-structural elements.
- Asset status.

- **Basic inspections (ADIF's standard: Basic inspection of bridges, NAP 2-4-0.0)**
  The standard gathers in more detail the methodology to follow when performing the basic inspection of a bridge and the way the information will be gathered and processed. Regarding the methodology, the document includes a catalogue with all the main assets to be inspected and the standard way to name them, the criteria to define a damage intensity level, a guideline on the itinerary of the inspection, and the methodology to categorise the damages and the level of importance of the damage, which depends on the type of damage, the affected asset and the level of intensity.

  All the information collected by the inspector will be uploaded to Adif's systems for its processing and the definition of:

  - Severity level of a defect.
  - Status of an item.
  - Asset status.

  These parameters that will determine the evolution of the defects when comparing them with the previous inspections.

A2.6-1.2 Current Practices: bridges in roads

The Spanish Road Directorate that belongs to the Ministry of Transport, Mobility and Urban Agenda (MITMA) has consistently had the concerning for the maintenance of the bridges over the time. A Roadway inventory was created in the 1960, but it was in 1980 that a specific bridges inventory was originated with some information regarding the length, functional, structural and geometrical features. This inventory was completed in 1993, and it has been updated since then. 1980 was the year in which the back then Ministry of Public Works published the "Main inspection for bridges in highways", pioneer in defining the different types of inspection, periodicity and the areas of inspection. However, in 1990 the implementation of the SGP (System for bridges management) boosted the inspection for bridges in highways in a relevant way, the system collects and improves the systematic of the inspection and execution more specifically, in line with other countries:

- establishing prioritisation of reparation
- defining the alternatives of reparation
- control and follow up of the actuation

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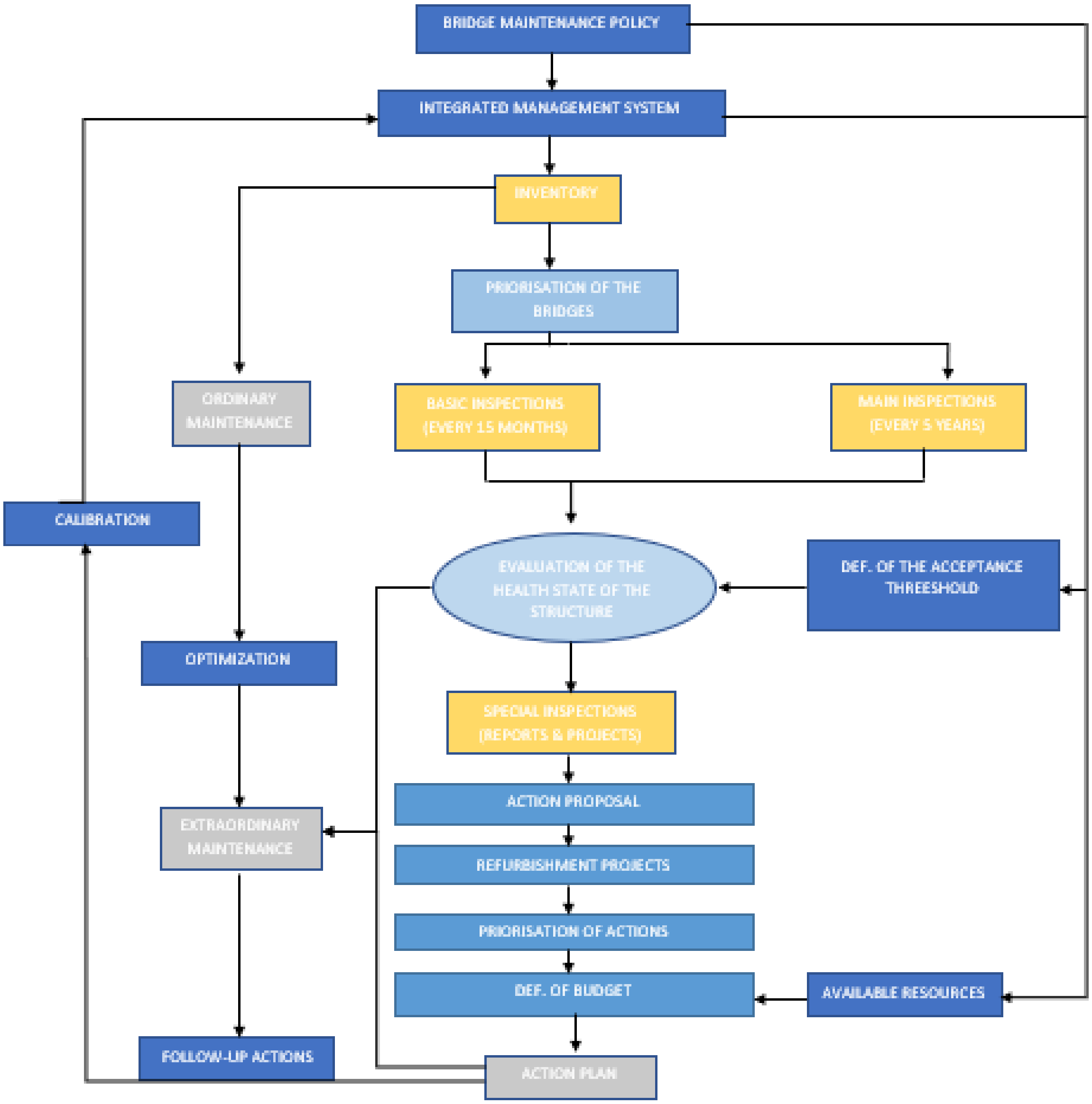

Figure A2. 1 - SGP: Spanish System for Bridge Management

Scope
(1) Create the inventory of all bridges
(2) Categorize every structure per importance
(3) Basic inspections and main inspections
(4) Evaluation of the health state of the structure
(5) Evaluating the need of special inspections
(6) Action and rehab projects
(7) Establish prioritisation of actuation
(8) Definition of budget
(9) Defining the ordinary and extraordinary maintenance
(10) Creating the action plan
(11) Follow up of actions

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This scheme in Figure A2. 1 comprises the following types of inspection:

- **Basic inspections:**
  It is a visual inspection to detect early deterioration and to prevent it to degenerate in more serious problems. Also, it allows to detect important deterioration that require urgent reparation.
  - Periodicity: every 15 months
  - Inspection technologies: not specified, only visual inspection is required
  - Inspection procedure: the basic inspection consists of the following aspects:
    - Bridge roadway and accesses: bumps, non-well compacted areas, transition slabs with damages, earthworks erosion, etc.
    - Sidewalk: presence of plants, damages on the surface, etc.
    - Railings and barriers: vertical and longitudinal alignment, crashes, corrosion, state of anchors, etc.
    - Dilatation joints: state of coating, cleaning, weathertightness, noises, broken or lost elements, etc.
    - Bearings: excessive deformations, longitudinal and transversal movements, state of concrete beam support, etc.
    - structural deck: cracks, exposed reinforced, spalling, aggregation, moisture, structural damages, etc.
    - Abutment and piers: Crashes, cracks, spalling, horizontal movement, exposed reinforcement.
    - Foundation: erosion, socavation, collapses, etc.
    - Drainage systems: cleaning and general state.
  - Inspection outcome: the following information has to be included in the Basic Inspection Sheets:
    - General data of the structure: code and name of the bridge (there is a specific legend to do it), main road, and road which is crossed, main location, UTM coordinates, class, typology, characteristic material, number of spans, length, width.
    - General data of the inspection: date, company, realized by, revised by, general observations, recommendations,
    - Observed damages per element and type of structure:
      - Critical damages and anomalies on the structural elements
      - Critical damages on the bearings
      - Damages on the expansion joints
      - Damages on secondary elements
      - Inadequate functioning of the drainage systems
      - Signalling and barrier deterioration
      - Lighting problems
      - Damages on transition slabs
      - Vandalism, graffitis, etc.
  - Damage classification.
    - The observed damages will be classified as: (A) Acceptable, (RN) Reparation Needed, (UR) Urgent Reparation

- **Main inspections:**
  The objective of the Main Inspection is to detect the existing damages of the different elements. It consists of a detailed supervision of all visible elements that do not require special auxiliary access means. The results of the Main inspection are delivered in a series of Primary Inspection Sheets, and a state index or condition mark is assigned to each structure.

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- Scope: all type of bridges and underpasses: deck supported by piers / abutment, arch bridges, vault bridges, concrete frame structures, tubes, tied bridges, suspended bridges (Any construction material)
- Periodicity: every 5 years (depending on the importance of each bridge)
- Inspection technologies: to carry them out, simple auxiliary elements will be used: ladder, hammers, plumb bobs, tape measures, optical devices
- Inspection procedure: the information has to be included in the Main Inspection Sheets.
- Three types of inspections are explained: perimetral lower inspection, zig-zag lower inspection, upper inspection.
- Data:
    - General data of the structure: code and name of the bridge (there is a specific legend to do it), main road, and road which is crossed, main location, UTM coordinates, class, typology, characteristic material, number of spans, length, width.
    - General data of the inspection: date, company, realized by, revised by, general observations, recommendations,
    - Observed damages per element and type of structure:

    The methodology of the inspection of the crossing river is also included in the present guideline.
- Inspection outcome: Report (standard form)
  The collected data is the following:
    - General information about the inspection: type of structure, date, person in charge, access means, climatology, etc.
    - Photographs
    - Information about the current conservation state
    - Illustrative photographs of the damages
    - Final results filled in the inspection sheets
- The elements to be inspected:
    - Foundations
    - Substructure: abutments, piers, bearing pads
    - Superstructure: main and secondary structural elements (beams, frames, purlings), and compression slab
    - Equipment: expansion joints, walls, waterproofing, pavement, drainage system, signaling, etc.

    It also includes the particularities of the inspections under water.
- The type of damages is classified by the type of structure:
    - Aspects related to the project: (1.1) structural typology (influence of the structural behavior, influence of the plan and longitudinal geometry, influence of the type of expansion joints and bearing pads), (1.2) transversal geometry, (1.3) age of the bridge (code, materials).
    - Damage mechanisms: (2.1) General scheme of damage mechanisms: physical, chemical, corrosion, during the construction, structural, (2.2) Vulnerability against seismic forces (seismic hazard zone, anti-seismic devices).
    - The damaged element: (3.1) foundation (loss of covering material, differential settlement, scour), (3.2) Abutments (erosion, glissade, settlement, overturn, excessive pressures), (3.3) Protective elements, (3.4) Piers (settlement, longitudinal and transversal twist, cracking (shear, compression, buckling, bending moments), (3.5) Superstructure (beams, boxes, slab, etc.) (deformation, corrosion, all different types of cracking (diagonal, longitudinal, transversal, vertical, horizontal..), (3.6) Masonry bridges, vault bridges, tied bridges, suspension bridges.

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  - Connecting elements: (4.1) Bearing pads (corrosion, lifting, loss of original position, excessive compression, excessive deformations), (4.2) expansion joints (degradation, impeded movement, loss of material, presence of plants, breaks, seepage).
  - Sidewalks, drainage systems, railings, barriers, signaling.
- The type of damages is classified by the type of material:
  - Concrete: (1.1) Accidental factors: high speed water, de-iced and ice action, salt crystallization, chemical factors (efflorescence, chemical attack, alkali reaction, pure water attack), biological attack (plants, microorganism), (1.2) Corrosion of steel bars, (1.3) Cracks.
  - Steel elements: corrosion, humidity, loss of painting, joint damages.

- **Special inspections:**
  In this type of inspections, in addition to carrying out a visual inspection, characterisation tests and complementary measurements are needed. This level of recognition requires a plan prior the inspection, detailing and evaluating the aspects to be studied, as well as the techniques and means to be used. In these types of inspection is needed a characterization and evaluation of damages assessment, and a project of reparation.

  Some examples of particular inspections are:
  - Geotechnical analysis with extraction of samples
  - Evaluation of concrete resistance by extracting concrete samples
  - Ultrasound tests
  - Evaluation of steel resistance by traction tests
  - Electric Power measures to check the corrosion of the steel bars

  They are not realized systematically or periodically. They are normally performed as a consequence of the damage detected in a Main Inspection.

A2.6-1.2 Current Practices: tunnels in railways

ADIF, the Spanish state-owned railway infrastructure manager under the responsibility of the Ministry of Transport, Mobility and Urban Agenda (MITMA), has its specific standards for inspecting tunnels in railways, for this purpose, the information is bifold in two standard documents depending on the type of inspection:

- **Basic inspections (ADIF's standard: Basic inspection of railway tunnels, NAP 2-4-0.1)**
  The standard NAP 2-4-0.1. created in 2020 by ADIF (Spanish state-owned railway infrastructure manager) describes the basic inspections of railway tunnels, specifying railway tunnel as an excavation or construction around the tracks that allow the railway to pass, for example, under the ground, buildings, or water, or even under other tunnels, and the tracks being totally confined. The basic inspections consist of a visual observation of the tunnel elements to monitor their general condition, allowing to detect as soon as possible, and without waiting for the next scheduled main inspection, the appearance of any real or apparent damage susceptible of monitoring or repairing.
  - Scope: railway tunnels (any construction material, such as, concrete, rick, masonry, ashlar.
  - Periodicity: not specified in this standard. The inspection schedule is included in the preventive maintenance procedures.
  - Inspection technologies: lighting equipment, measuring elements (tape measure, flexometer, optical distance measuring instrument), fissure meter, binoculars, hammer and knife, camera, etc.
  - Inspection procedure: Visual observation of the tunnel elements.

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The standard includes the methodology to be followed to carry out the basic inspections by the inspector, who is in charge of observing all the elements of the asset to visually detect the existence of damage, assigning to each detected damage an intensity that will express the state of progress or the extension of the damage. Afterwards, this information will be processed to obtain some indicators that allow optimal asset management.

- Inspection outcome: The output of the inspection will be summarised with the following indicators:
    - Severity level of a defect.
    - Status of an item.
    - Asset status.

  From these data, the evolution of each of the indicators will be determined by comparing them with the previous inspections.

- **Main inspections (ADIF's standard: Main inspection of tunnels, NAP 2-4-1.1):**
  The standard NAP 2-4-1.1. created in 2020 by ADIF (Spanish state-owned railway infrastructure manager) describes the main inspections of railway tunnels. The purpose of the main inspections is to obtain information on the functional and resistant state of a tunnel at a given time, in order to verify that it is capable of fulfilling the function for which it has been built, with an acceptable level of safety. The main inspection will always be performed after having the information of the basic inspection. The main inspection is a deeper reconnaissance of the tunnel itself.
    - Scope: railway tunnels. This standard also includes structures that create a confinement of the tracks in a length greater than 50 meters. This confinement must always be, at least, above the tracks and on one of their sides, and it may be open or partially open on the other side of the tracks.
    - Periodicity: not specified in this standard. The inspection schedule is included in the Preventive maintenance procedures. If through a main Inspection it is detected that the inspected asset or any element requires immediate corrective maintenance, it will be communicated immediately. The inspector, based on the potential degradation rate, will propose to modify the tunnel maintenance plan, reducing if necessary, the period for carrying out the main inspections.
    - Inspection technologies: Laser scanner equipment. All elements in which data collection cannot be carried out with the laser scanner equipment must be visually inspected. Measuring elements (tape measure, flexometer, optical distance measuring instrument), fissure meter, ladder, binoculars, hammer and knife, Camera with optical zoom of at least 24x, flash with enough power to reach a distance of 5 meters, GPS and sprays.
    - Inspection procedure: The main inspection of the tunnel will be carried out with a laser scanner on a rail trolley, which allows its movement at a speed low enough to detect all the elements. At the same time, the inspection staff must carry out the same route on foot, to visually observe the defects with the use of auxiliary means if necessary, as well as take pictures. All elements in which data collection cannot be carried out with the laser scanner equipment must be visually inspected.
    - Inspection outcome: The inspector, based on the defects detected during the Main Inspection, will draw up two action proposals:
        - Proposal to eliminate the defects that cause severity levels 3 or 4 (maximum).
        - Proposal to eliminate all the defects of the tunnel.

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A2.6-1.3 Current Practices: tunnels in roads

The “Orden circular 27/2008” regarding the “Methodology for the inspection of tunnels” published by the Ministry of Transport, Mobility and Urban Agenda (MITMA) in 2008 established the procedures in terms of maintenance for tunnels in roads. The main goal of the tunnels inspections consists of determining that the equipment, installations, and the structure comply with the code, checking that the infrastructure manager has enough material and human resources with the adequate training, supervising the type and the scope of the simulacres, developing a report of inspection results to conclude the state of the infrastructure and the corrective measures to be performed.

- Scope: road tunnels of any construction material.
- Periodicity: The periodicity of these inspections depends on the length of the tunnel:
  - Tunnels with a total length less than 500m: every 5 years (maximum)
  - Tunnels with a total length between 1000 and 2000m: every 4 years
  - Tunnels with a total length bigger than 2000m: every 3 years
- Inspection technologies: to measure the CRT (cathode-ray tube) index, a SCRIM (Sideway-force Coefficient Routine Investigation Machine) equipment is used.
- Inspection procedure: The methodology of the inspection will focus on the following aspects:
  - Civil works: to ensure the performance of the structure
  - Equipment: to verify the correct functioning of the equipment
  - Resources: to validate if the manager of the tunnel has the material and enough available personnel
- Inspection outcome: There are several inspection sheets templates as part of this guideline to check all the elements mentioned above. Basically, the guide suggests completing the information in a database. They have different rows to fill in the asset checked, its state, comments, etc.

Besides, in this guideline, there are several keys to be analysed such as: communications, electricity, lighting, ventilation, fire detection and extinction, emergency exits, radio communications, signaling and traffic control, etc.

A2.6-1.3 Current Practices: road bridges and tunnels monitoring standards

The Spanish Road Directorate has developed CELOSIA (http://www.celosia.es/), a platform for monitoring and analysing in real time the monitored structures in the Spanish Road Network. This platform backs the digitisation of infrastructures that must lead to an improvement in the management of their conservation and, of the safety conditions of the users. The objective of the platform is to provide to the instrumentation systems of the Spanish Road Network structures with a common support for communication and data visualization, centralising the information and standardising the formats so that the content is homogeneous regardless of the technology used and easily accessible to all the technicians involved in structural surveillance: construction managers, technical assistants, project offices, construction companies, preservation teams and instrumentation companies. Today, it is mandatory to integrate all structures (that belong to the Spanish Road Network) that have an electronic control instrumentation system into the CELOSIA platform. The platform allows access to information in real time. Any experimental data measured must be uploaded to the database and will be made available on the web platform in a few seconds. The system is automatic and has a messaging service to send any kind of notifications. The contents are generated and presented at the request of the users, always updating the latest available data. The central engine of the platform combines the experimental data with the variables and internal algorithms necessary to produce a higher level and useful content.

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References of the Structures general overview are shared by CELOSIA Platform: www.celosia.es

The system used saves the information through a single database, preserving the content beyond the life of the monitoring system. Therefore, the data contained in the platform has multiple uses, ranging from the control of manoeuvres and monitoring of construction aids (short term) to monitoring the evolution of pathologies (medium term) or the detection of behaviour patterns (long term). In other words, CELOSIA improves the understanding of infrastructures. The Celosia platform shows the structures that have been or are being monitored. In accordance with the Orden Circular 2/2021 regulation, about the structure monitoring platform of the Spanish Road Network, all the elements of the Spanish Road Network (bridges or similar, embankments and tunnels) that have an electronic control system will have to integrate their data into the CELOSIA platform according to the protocol explained in that standard (the protocol describes how new assets should be registered in the platform, the data types, files type, data uploading, measurement frequency, and further definitions, to make sure that all data follow the same structure).

The Vinalopo bridge is a good example to illustrate the use of CELOSIA platform. The Vinalopo bridge (in Elche, Spain) is one of the few complete steel bridges in the Spanish Road Network, therefore, there is little information available on the thermal behaviour of this type of decks. Since 2015, a thermal monitoring system has been placed, in order to be able to detect extreme temperature episodes.

A2-6.2 Needs and challenges

A high need of including preventive and even predictive strategies in the maintenance plans is outlined. Hence, the Spanish CoP highlights the necessity to provide strategies for measurements and continuous data collection in specific places. The objective is to know the real time evolution and to be able to define alarms in infrastructures, like it is already being done through CELOSIA platform in some structures as previously explained. The key aspects highlighted were around technology, monitoring with sensors, data and data sharing.

- **Technology:**
  Standards need to adapt more quickly and instead of slowing down the introduction of new technologies that are safe, proven and would help improving the way people work today.

- **Monitoring with sensors:**
  The main concerns are related to:
  - Standardization and certification of data collection equipment
  - Amount of data
  - Ability to manage the volume of data.
  - Definition of appropriate thresholds.
- **Data:**
  The main question that arises at this point is to understand what data is relevant and also the need of using open source software, so that data is easily accessible and available. Assets monitoring is key, however it is clear that it is not necessary to monitor everything. But what are the most critical aspects to monitor? The CoP outlines that it is necessary to detect which elements are the ones that really generate a risk in the infrastructure. But, how to identify them? Each bridge or tunnel is different, a unique and complex structure.

- **Data sharing:**
  The CoP stated that improving the way in which infrastructure data is made available to all interested parties (administration, maintainers, operators, research centers, etc.) is needed as well as improving the information made available for the infrastructure user.

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A2-6.3 Trends

A2-6.3.1 Trends: roads

There are cases of continuous and temporary monitoring during assets operation and also monitoring during the construction phase. CELOSIA platform, as previously stated, is gathering the DATA of the structures that are being monitored and boosting the use of monitoring systems and data gathering and analysis. The platform is not bound to any specific kind of technology, but some of the technologies that have been used to monitor data are:

- IoT - Thermal monitoring
- IoT – Vibrations monitoring with accelerometers
- IoT – Position monitoring, landslides monitoring

Besides CELOSIA, there is also another platform that is currently being developed by Ferrovial Construction for its internal use in the construction sector in which not only the structure is being monitored and the data is gathered but also, the information is linked to the BIM model of the structure itself. The following knowledge and global objectives have been achieved so far:

- Connection of the auscultation system and its information collected in the 3D design of the bridge following the guidelines of the BIM methodology.
- Treatment and processing of the data received from different existing sources.
- Definition, design and development of a data model that allows its integration in BIM systems (IFC-type files).
- Inclusion of the historical data of the sensor applied in the bridge to the BIM model.
- Development of a platform that integrates all the functionalities needed and serves as control and monitoring of the BIM model in which all the data and historical measurements associated are included.

A2-6.3.2 Trends: railways

There have been cases of temporary monitoring, in operation and construction phases. The railway sector needs solutions that increase safety and efficiency in the transport of people and goods, reduce maintenance costs and improve its competitiveness. Optimizing asset maintenance is essential for the rail system to function safely, reliably and sustainably. Having exact information on the elements of the infrastructure is of crucial importance in creating an environment that favors maintenance decisions, the ultimate goal of which is to guarantee a level of quality at all times in accordance with operating requirements. It is a change in the way of approaching maintenance processes that goes through overcoming the periodic preventive and reducing the corrective as much as possible. Some of the R&D projects in which ADIF, the Spanish state-owned railway infrastructure manager, has been involved are:

- Tunnel Curiosity - Unmanned automated inspection vehicle in which data capture systems and information processing elements were integrated, for railway tunnels, optimizing maintenance and consequently the safety of the railway infrastructure
- Sentinel - New pilot prototype for a smart system for managing railway infrastructure by using structured big data. The project, which began in July 2016, aimed to integrate a data-capturing device into maintenance vehicles for railway lines and feed a database with a corresponding system of geographical information. That way, it can update an automatic or semi-automatic inventory of railway assets, at the same time as it reviews and evaluates parts of the railway, thereby optimizing maintenance operations. It consisted in integrating Lidar systems (which obtain 3D maps and images of the railway though dynamic scans by using technology called mobile mapping systems), GPS, cameras, and high-precision recorders, lighting, etc. All these allowed digitalizing this new infrastructure at a traveling speed of 80 km/h on a maintenance vehicle equipped for the tests.

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- Transforming Transport – predictive maintenance in the railway sector using big data based on the data obtained from ADIF's monitoring train.

In ADIF's innovation strategy, permanent monitoring has been identified as a priority line of work that would allow to gradually migrate to more predictive maintenance or maintenance based on the condition of the asset itself. The Public Purchase of Innovation (CPI) is a tool to promote innovation from the public sector through the acquisition of innovative solutions or solutions in the development phase. The main objective of this contract is to obtain technological solutions that are capable of detecting structural damage in early stages and generating tools to be able to apply predictive maintenance strategies. Currently, they are working on:

- The automation of auscultations: Technological solutions for predictive maintenance of bridges and viaducts, a project divided in 3 phases:
    - PHASE I: Solution design
    - PHASE II: Development of a prototype or tests of the proposed solution
    - PHASE III: Pre-operational verification

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A2-7 Portugal

A2-7.1 Current Practices

This section contains a brief overview of the main current practices in Portugal. In terms of bridges and tunnel inspections and monitoring, there are no national regulations defined. However, Infraestruturas de Portugal, which is the state owned Portuguese general concessionary for roads and railways that was formed in June 2015 from the merge of the former road general concessionary and railway general concessionaire, has developed their own procedures defining the type, the frequency and the protocol of inspection to be carried out in order to comply with the state defined objectives and indicators (average condition of bridges and tunnels) and a new harmonized management system (SGOA) is envisaged to harmonise the management of railways, and roads bridges and tunnels.

In Portugal, there is a large territorial dispersion regarding bridges and tunnels with different construction periods, materials and construction techniques (only in roads managed by IP, there are 5800 bridges and tunnels).

The following picture shows the framework which contains the main activities regarding inventory, inspections, monitoring and the condition state attributed for each inspection.

For the main activities regarding the inventory, the type of inspections defined are:

- **Periodic visual inspections**: these inspections are divided in routine inspections and principal inspections. Routine inspections are related to maintenance activities, and it is necessary to define the current maintenance status, the current repair status and provide alerts for traffic safety. Principal inspections are performed to define the asset condition-state to prioritise interventions. These inspections are more in-depth inspections conducted by a civil engineer with a wide knowledge and experience in inspection and infrastructures. There are six condition states that allow to define three types of surveillance: normal surveillance, reinforced surveillance and high surveillance. These kinds of surveillances are used to define the periodicity of subsequent inspections.
- **Special inspections:** these inspections are carried out when needed.

The bridge management system and the inherent process has been developed since 2003, and has been fully implemented since 2007 (Horta & Freire, 2013). Besides, this framework and protocols are not closed, since the beginning of their implementation they have been opened to the experience, knowledge and lessons learned.

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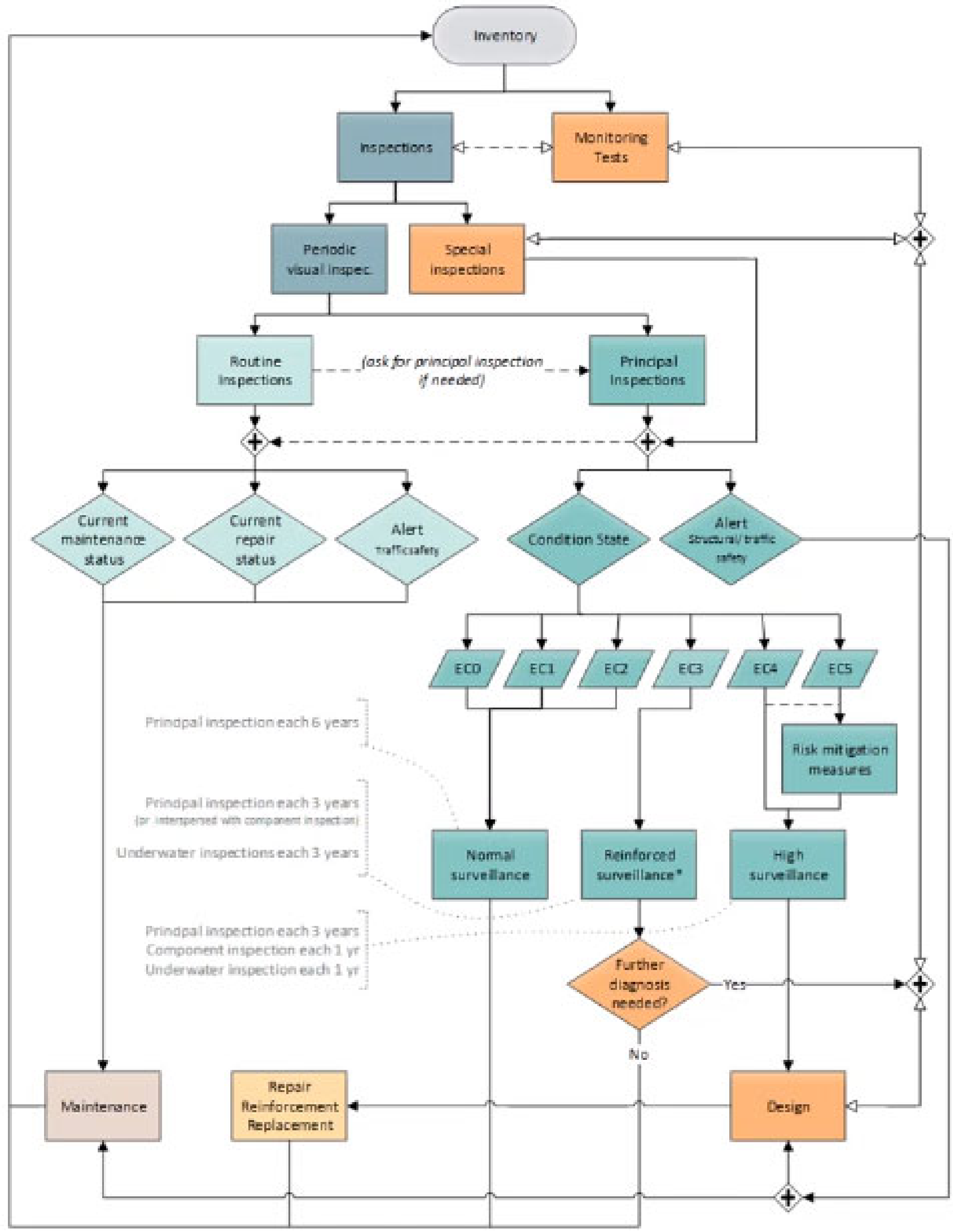

Figure A2. 2 - Scheme of the Internal Regulation for Bridge and Tunnels inspection (IP) (interpreted from (Povoa A. Freire, 2019))

The common techniques/technologies applied to complement these inspections are:

- Defects mapping
- Thermography
- Underwater bathymetry

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- SONAR (Sound Navigation And Ranging)
- Geometric surveillance
- Static laser scanning
- Tunnel convergence measurement
- Fiber optic sensors
- NDT tests:
    - Cover meter and bar detection
    - Carbonation depth and chloride content
    - Rebound hammer
    - Ultrasonic tomography (most uncommon)
    - Ground penetrating radar
    - Ultrasonic measurements and half cells potential

Landmark bridges (there are more than 20, i.e. Guadiana bridge) are using long-term monitoring for structural behaviour with the following characteristics:

- Strain and deformation measurements
- Thermal gradients
- Rotations
- Expansion joints width
- Creep and shrinkage
- High precision leveling

The asset management landscape at Infraestruturas de Portugal, IP, includes the following :

- An Enterprise Asset Management software “RADAR”. It is an internal software for maintenance investment needs for all asset groups.
- An Asset Performance Management system “SGOA”. Based on a commercial software that manages condition data, defects recording, notifications, alerts.
- An Asset Investment Plan. An internal protocol for investment prioritization.

A2-7.2 Needs and Challenges

Needs:

- The necessity to harmonise roads and railway asset performance management software and to include financial capabilities. Essentially, to upgrade the asset management system and to ingrate rail and road in only one protocol.
- Increase the ability to analyze risk and integrate results into the prioritization algorithm.

The main challenges identified in Portugal are the following ones:

- BIM technologies as a way to enhance capabilities mainly for repository and prediction and to enhance preventive maintenance but for this there is a need to adapt or upgrade the inspection protocol to support BIM technologies.
- The focus on new structures disregarding the maintenance of existing structures.
- The lack of national or European standards that establish the protocols for inspection, diagnosis and maintenance.
- Climate change new demands on the resilience of structures.
- Rapid technological development that requires a policy of continuous investment and continuous awareness.

A2-7.3 Trends

Some of the ongoing exploratory projects are:

- Set of Drones for inspection (used for different infrastructures)
- Mapping Software (training their operators)

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- In2Track2 and In2Track3: Fatigue models for steel bridges which are related with laser scanning and point cloud models using photogrammetry.
- UIC: drone for rail project
- PIARC: Technical Committee 3.3, which is related with asset management
-

Portuguese start-ups are dealing with the satellite's topic. In fact, there is a start-up that uses earth observation data and artificial Intelligence for infrastructure management, namely monitoring solutions based on satellite measurements, having benefited from the support of Copernicus European Union's Earth observation programme (https://accelerator.copernicus.eu/portfolio/matereo/). A retrospective analysis of the collapse of a bridge in Portugal (occurred in 2001) using satellites demonstrated the potential of the technique to detect and monitor deformations (Joaquim Sousa, 2013).

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A2-8 Latvia

A2-8.1 Current Practices

The SHM monitoring system in Latvia is still developing. The first road and bridge condition studies were carried out as part of a project at the University of Riga in 2017.

Obligation of inspection of roads, bridges and is required in General Construction Regulations (Vispārīgie būvnoteikumi - Latvijas Vēstnesis, 191, 26.09.2014). Duty of control is imposed on owner or local government.

Engineering facilities are reviewed once a year. This is to ensure the existing condition of the facility and its access to use. During the inspection are analysed:

- structural elements of the facility,
- traffic safety level,
- potential types of damage (including the road part and pedestrian / bicycle).

Generally, all inspection of engineering facilities must be documented by Annex 9 ("Opinion No.________ regarding inspection of the structure"). It is cared for by a person having the authority of a supervisor engineering facilities.

A commonly used program for collecting information on the health of bridges is a BMS system (Bridge Management System). Latvia has its own program, LatBrutus. It was developed with the support of Norwegian bridge specialists, and the program itself was approved in 2002. It consists of the 4 modules:

- Module of inventory;
- Module of inspection;
- Module of maintenance;
- Codes and system administration

Inventory module has all necessary data about all bridges in road network to obtain the necessary technical information. On the other hand, module includes database for inspections and maintenance. The inspection module collects information on planned inspections and records data on the technical condition of the bridges during their operation. The maintenance module helps to prioritize implementation and financing. The administration module is necessary for the general division of users and reports.

The most popular inspection of the bridge in the LatBrutus system are visual inspections. All inspections are classified:

- Commissioning inspection – transfer of the structure to maintenance, in other words it is could be initial inspection after construction or in the beginning of maintenance actions.
  Guarantee inspections – inspections that are done at the end of guarantee period.
- General Inspection – annually or more frequently made inspections.
- Main inspections – inspections done at least once in five years.
- Special Inspection – is completed to test, monitor a known defect or condition.

A2-8.2 Needs and Challenges

The main objective of Latvian Transport Policy is to establish a sustainable transport system which meets society's economic, social and environmental needs. The Latvian rail network needs considerable restoration (about 30% of railways need to be reconstructed).

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The same situation is on the road. Most roads require reconstruction and rebuilding. Generally, it is an economic problem. Insufficient funds are earmarked for public and express roads. In the case of road tunnels, the situation is not so clear. It is related to a small number of such engineering facilities.

In Baltic countries the bridge management systems are very similar. They have similar modules and purposes, but with different visual assessment levels and condition states. It is possible to compare some data analysis with multivariate analysis. Unfortunately, Latvian data needs some additional work.

A2-8.3 Trends

SHM monitoring system in Latvia it is still under expansion. SHM system is designed to help find early design flaws, e.g. cracks, deformation, materials degradation or fatigue. There are many non-destructive techniques practiced, such as:

- ultrasounds,
- Fibre Bragg Grating,
- acoustic emission,
- vibration-based methods (Operational Modal Analysis).

In the last year was renovated some bridges. One of them was bridge over the Gauja River near Murjani. It was replaced by a concrete twin rib deck. The span of this bridge has the continuous multispan structure: 21,85 + 4 x 22,2 + 21,85 meters. There was used a method of incrementally launched deck, what should be verified by some analysis method.
The other bridge which also has SHM system is Dienvidu Bridge over the Daugava River. The structure of that bridge also has multispan structure: 49,5 + 77 + 5 x 110 + 77 + 49,5 meters which is adopted by extradosed system (6 traffic lanes). The structure has a continuous twin steel box with composite concrete deck.

Both bridges were tested by static load test and dynamic load test. Static load measures the deformation and force values. Measurements are made:

- vertical deformation (in middle and in other points of bridge);
- displacements of pylons.

However dynamic load tests give useful information about behavior of the bridge under traffic. In that case the main characteristics of the structure are:

- fundamental vibration frequency,
- dynamic amplification factor,
- logarithmic decrement.

The data obtained from these measurements made it possible to create a bridge supervision and maintenance plan. The system can also predict possible future damage to the structure.

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A2-9 Estonia

A2-9.1 Current Practices

Estonia is one of the Baltic countries with the least experience in SHM monitoring system. The implementation of the unified control and management system started in 2003 and was introduced in 2005. Currently, Pontis software, which was developed by the consulting company Teede Tehnokeskus, is used. The database of this program collects information such as:

- data on the condition of the bridge,
- traffic needs,
- data about accidents,
- maintenance costs,
- available financial resources.

Such information was collected until 2013, when the Estonian Road Administration took over the management of the bridges at its own risk. BMS in Estonia is based on four different modules:

- inventory module,
- inspection module,
- cost module,
- analysis module.

Inventory module consists of metadata like bridge dimensions and construction information. It is based on national road registry and is updated simultaneously. Inspection module consists of inspection data like element conditions and inspection dates. Cost module is based on the unit prices collected during procurement process. Analysis module takes all previous information and gives ranking list based on bridge condition, age, traffic density and measurement requirements.

The most common are visual inspections to assess the technical condition of bridges. They are performed at least once every 4 years. These are inspections of individual bridge elements, e.g. deck plate, edge beam, main girder.

A2-9.2 Needs and Challenges

Recent years have shown Estonia to perform well in terms of its financial health. The funds are allocated to public investments. Despite this, the quality of roads and bridges leaves much to be desired. It is related to Estonia's location on the map of Europe. The country is close to Russia and Finland, hence increased transit traffic can be observed there, both by trucks and rail routes. Despite the funds that are allocated to road repairs, it can be noticed that the needs are much greater.

One of the objectives of the current reform is also the introduction of new, innovative technologies in the field of assessing the condition of public roads and bridges. In Estonia, monitoring systems for engineering facilities are often used, which are easy to install and use. This is mainly due to the facilitation of road traffic.

A2-9.3 Trends

One of the examples of SHM monitoring is the use of the BWIM (Bridge Weigh-in-Motion) system. It is a tool that collects information about engineering facilities. It is able to determine the economic importance of a bridge, depending on the volume and type of traffic. The basic parameter that is tested is the deformation level of the bridge. The BWIM system measures the force exerted by each axle of the vehicle. This system is most accurate in the case of single-span structures made of steel or concrete.

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The main advantage of this system is the ease of its installation. The sensors are placed under the bridge, not like it used to be inside the road under construction. Thanks to this, the movement is not disturbed in any way, as well as the points where sensors are placed minimize damage to the bridge.

An example of a bridge on which the SHM monitoring system was used is the bridge near the town of Sanga, located on an accelerated road. It has a multi-span structure with a length of 36 meters. Moreover, it is made of lightweight concrete. The BWIM system was used here using the so-called Spider loggers. The Spider system can simultaneously monitor several sensors that measure different parameters. Most often they are:

- vertical deformation,
- displacements of pylons,
- fundamental vibration frequency.

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A2-10 Lithuania

A2-10.1 Current Practices

The Lithuanian Road Administration was the first among the Baltic countries to start the development of BMS in 1992. The last updated version is from 2016 and is still developing. The Lithuanian Road Administration used the knowledge of Swedish and Finnish Road Administration specialists. As a result, it was able to ensure the development of local experts and scientists involved in the prior auditing of roads and bridges. The BMS system is based primarily on the review and assessment of the technical condition of an engineering facility.

The Lithuanian BMS consists of the following modules:

- inventory data,
- inspection data,
- allocation (Budget) module,
- price catalogue,
- optimization,
- reports, photos, drawings,
- maintenance module,
- GIS,
- long-term planning.

Technical inspections in Lithuania are carried out annually, while the main inspection is carried out on average every 6-8 years. Comparing the Baltic countries, it can be concluded that each country has implemented a bridge management system appropriate for it. The overall approach to bridge management and monitoring is similar, while the decisions made differ from one another.

A2-10.2 Needs and Challenges

National roads in Lithuania create a network of connections between this country and neighbouring countries. The surfaces of both roads and bridges are mostly made of asphalt mixtures (approx. 59%). The basic need is the modernization of roads and bridges due to the increasing traffic intensity. As in Latvia and Estonia, the main problem is in economic considerations. Modernization is needed, but the funds for its implementation are still lacking.

The SHM monitoring system is extremely important, however, it carries high operating costs for the realities of the Lithuanian road administration. Hence, its wider implementation is quite limited.

A2-10.3 Trends

An example where the SHM monitoring system was used in Lithuania is the bridge along the Kaunas-Kybartai railway line over the Sesupe River. The bridge is made of prestressed concrete sleepers and crushed stone ballast. This is an example of a multi-span bridge with a total length of 52.40 meters and 11.82 meters in width. The longest single span is 32 meters long. The sensors were located along the entire length of the bridge as well as pointwise. The collected data made it possible to obtain information on parameters such as: vibration frequency, vertical deformation and displacements. An important factor is also visual inspection, which is increasingly done with the use of drones.

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A2-11 Czech Republic

A2-11.1 Current Practices

The standards present in the Czech Republic do not precisely define the principles of SHM monitoring. As in other countries of Eastern Europe, this is a relatively new topic. It is most often used in the case of highways, where the traffic intensity is highest.

There are four types of inspection for engineering structures such as bridges or tunnels:

- Routine checks performed on accessible elements every 6 or 12 months. It depends of bridge condition.
- Main checks which is dictated by checking all elements of the bridge. If the bridge is in bad condition control should be done every 2 years, 4 years if bridge is in medium condition or every 6 years in good condition.
- Extraordinary checks which is dictated when on the bridge was an accident or flood.
- Control inspections which are conducted with three others control and should be done every 6 years.

All these inspections are located in CSN 73 6221 standard and are performed visually.

A2-11.2 Needs and Challenges

As in the case of the Baltic states, the main factor that influences the improvement of the road infrastructure is the economic factor. Most of the funds go mainly to public procurement, but they are still too low.

An extremely important challenge faced by the Road Administration is the introduction of innovative technologies to monitor the technical condition of engineering facilities, so that these are not only visual measurements.

A2-11.3 Trends

Recent years have shown that the SHM monitoring system most often covers newly built expressways, as well as multi-span bridges with high traffic.

They are commonly used as DFOS fiber sensors. They are quite innovative due to their direct integration with composite elements. Commonly are measured values:

- angular displacements,
- deformations,
- frequency vibrations,
- linear displacements.

Most often, during the visual inspection of the bridge, cracks can be observed, in particular:

- Importance of cracking with respect to materials and serviceability requirements on structure,
- Estimation of development of damage and resistance of structure in the area of cracking,
- Local conditions in area of cracking (position and types of cracks).

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A2-12 Slovakia

A2-12.1 Current Practices

As in the case of the neighbouring countries, the situation with the monitoring of engineering facilities in Slovakia is very similar. There is no clear standard for monitoring bridge structures. However, there are standards that describe bridge inspections and their diagnosis. Information on inspections is included in the standard TP 08/2012 (*Ministerstvo dopravy vystavby a regionalneho rozvoja SR, 2012b*) and TP 07/2012.

TP 08/2012 standard specifies the following inspection methods:

- routine annual visual inspections of all available bridge components,
- general inspection of overall bridge structures every 4 years,
- special inspections, which are performed when a road collision occurs, as a result of which the geometry of the bridge may change,
- visual control inspection as a result of an emergency.

Whereas included in the TP 07/2012 standard the following types of bridge diagnostics are included:

- informative,
- standard,
- detailed,

which are performed only at the request of the owner as visual, destructive or non-destructive test.

A2-12.2 Needs and Challenges

Compared to neighbouring countries, Slovakia has much fewer expressways, and thus also bridges. However, Slovakia is crossed by the second largest river in Europe - the Danube. For this reason, it was decided to introduce a wider group of monitoring and technical assessment of bridges. Mainly SHM monitoring systems started to be placed on multi-span bridges where the traffic volume is higher (e.g. Port Bridge and Slovak National Uprising Bridge). They are one of the most important bridges in Bratislava where transit traffic takes place. As in the case of the Czech Republic, the main need is finances, which in Slovakia are allocated primarily to industry and education. Another challenge is the introduction of innovative monitoring techniques that are not cheap.

A2-12.3 Trends

The first works on the implementation of the monitoring system appeared in early 2000. Recent years have shown that the most frequent measurements are: deformations, frequency vibrations and linear displacements.
One of the examples where the SHM monitoring system has been used is the Port Bridge. It is a steel railway bridge located in Bratislava on the Danube River. The bridge was put into operation in 1985, it is part of it:

- main bridge construction,
- motorway and railway flyover,
- footbridges for pedestrians and cyclists.

It is a multi-span bridge with a total length of 461 meters.

Another example where the SHM system was used is the Slovak National Uprising Bridge. It is a cable-stayed, steel bridge located under Castle Hill in Bratislava over the Danube River. The construction of the bridge was completed in 1972. This bridge also has a multi-span structure with a total length of 432 m.

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In both cases, FEM models of these bridges were created on the basis of beam and shell elements. Additionally, in the case of the SNP bridge, it was necessary to take into account the curvature of its bridge. Thanks to this, it was possible to create the so-called a digital twin where it was possible to mark specific places where any defects could have occurred.

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A2-13 Romania

A2-13.1 Current Practices

From the 1980s, awareness of the deterioration and inefficiency of civil infrastructure systems began to grow. In 2016, it was found that an average of 5 people die on the roads every day, and this number is growing every year. The development of infrastructure in Romania, along with the aging of the existing infrastructure, has increased the importance of monitoring the current state of engineering facilities.

Thanks to many debates and conferences, it was possible to define a strategy that will help to develop and then implement SHM monitoring in public life. This system would be represented by:

- the process of conventional inspection,
- inspection through a combination of data acquisitions and damage assessment,
- unifying the combination of non-destructive and structural characterization tests.

The system works primarily on the basis of visual inspections. The success of SHM monitoring depends on:

- Design and implementation of the SHM based on a multidisciplinary team, which consists of experts and specialists in that field,
- Making decisions supported by data from the SHM system.

A2-13-2 Needs and Challenges

Since 2016, estimation has been made of the profits that an SHM monitoring system can bring. Its implementation would make possible:

- Reduction of control and maintenance costs by 25%
- 10% reduction in life costs of bridges due to the prediction of its service life already at the stage of its design.

A2-13.3 Trends

Recent years have shown an increase in interest in the SHM system in Romania. Romania is one of the countries where road deaths are quite high. Therefore, along with the construction of new engineering facilities, a structure monitoring system is additionally introduced.
An example of a bridge where sensors for measuring various bridge parameters are to be installed is the Braila Bridge over the Danube River. It is a suspended bridge with a total length of 2,194.3 meters and a width of 31.7 meters. It will consist of four lanes and two pedestrian and bicycle paths. The sensor system will consist of:

- 2D and 3D accelerometers,
- Fiber Optic Sensors (FOSs) measuring strain and temperature,
- Static 2D inclinometers,
- tri-axial anemometer,
- load measuring pin,
- air temperature sensors.

Additionally, static and dynamic GPS sensors will be installed on the bridge towers to control their movement.

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A2-14 Hungary

A2-14.1 Current Practices

Hungary, like their neighbours, has an aging road infrastructure. It is estimated that there are about 6,000 bridges throughout the country, the total length of which exceeds even 93 km. They are mainly made of reinforced concrete (86%), steel (12%) or plain concrete (2%). Their average age is 46.

Data collection and classification of engineering objects has been going on since 1965. In the 1970s, on the other hand, data sheets on the condition of bridges and the National Road Data Bank were introduced, which allows for the collection and storage of data.

Currently, data collection and subsequent analysis of the results are carried out using the PONTIS software. It is a system that builds on the existing systems in Latvia and Estonia. It consists of the MR&R module, which is responsible for maintenance, repair and rehabilitation. Thanks to the collected data, the system is able to determine the condition of a given object, and at the same time to prepare a ranking of bridges that should be repaired in the first place.

The PONTIS program is mainly based on the results of the bridge inspection. The condition of the engineering facility is inspected on average every 1-2 years in order to establish the actual condition of the bridge.

A2-14.2 Needs and Challenges

A significant part of the bridges in Hungary requires modernization. These are facilities built in the 1980s. Most of them have not yet been included in the construction monitoring. Only visual inspections are carried out. One of the needs would certainly be to increase the number of inspections on a given site. It is also necessary to increase the number of experts involved in the monitoring of structures.

A2-14.3 Trends

As in other countries, inspections of bridge structures are mainly carried out on the basis of visual inspections. The monitoring covers mainly newly built engineering facilities.

Fiber optic and string sensors are used for measurements. They are measured, such as parameters:

- angular displacements,
- deformations,
- frequency vibrations,
- linear displacements,
- forces.

Weigh-in-motion sensors are also used. They are designed to detect vehicles with exceeded permissible weight and collect information about the volume and structure of traffic.

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A2-15 France

In France many technical documents exist in the field of bridges and tunnels maintenance but the most relevant are:

- The guideline regarding inspection and evaluation, the ITSEOA (Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art, from 2010) that regulates the inspection and monitoring of most roadway infrastructure, including bridges, tunnels, culverts, etc. It was published in 1979 and update in 2010. Seven inspection categories are considered:
    - (1) annual visual inspection on visible elements
    - (2) assessment inspection carried out every three years on the entire structure as visual inspection
    - (3) detailed inspection on the entire structure performed every three to nine years as visual inspection or tests
    - (4) detailed inspection of specific elements carried out every three to nine years as visual inspection or tests
    - (5) initial detailed inspection carried out after the construction of the structure or after interventions performed on the entire structure as visual inspection or tests,
    - (6) final inspection of contractual guarantees carried out before the end of a contract on the entire bridge as visual inspection or tests, and
    - (7) inspection after sudden events performed on the entire structure.

  The last three inspection types are grouped as special inspections. Inspections (6) and (7) are performed by expert personnel.
- IQOA guides (Evaluation of bridge condition for a better maintenance policy. IABSE Int. Symposium "Extended the lifespan of structures) which present the IQOA classification for each kind of deterioration and damage encountered on some types of structures, it defines the condition ratings as well.
- Repairs and strengthening (with the European standards of the EN 1504 series for repair products, the French standards of the NF P 95-100 series for the execution of repair techniques, the various LCPC (Central Laboratory for Roads and Bridges) technical guides on repair and protection of structures (IABSE Symposium 2019 Guimarães: Towards a Resilient Built Environment - Risk and Asset Management March 27-29, 2019, Guimarães, Portugal), and more recently the guides developed by STRRES (www.strres.org);
- Management (with management methods such as the VSC method, the departmental method, ..., and adapted software like SIAMOA, OASIS, SCANPRINT, AERO ...). The French maintenance management system, LAGORA, includes bridges, culverts and retaining walls. Tunnels are managed by CETU.

In terms of trends, there's an intriguing effort to use a cutting-edge SHM system called Bridge Watch Solution to handle the challenge of storing massive volumes of raw data and giving extensive structural state assessments. Two historic cable-stayed bridges, the Pont de Normandie and the Pont de Tancarville, are included in the proposal, as well as a rigid steel-framed bridge over the Grand Canal Viaduct, the Pont sur le Grand Canal du Havre (Fisher, 2018). Another interesting endeavor is a case study of monitoring a scour-affected bridge using bathymetric and water level measurements.

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A2-16 United Kingdom

In this country, SMIS is the system management information. It is a database that underlies the user interface for bridge management with functions as: control of inventory data, deterioration modelling, assessment of maintenance needs and costs, and evaluation of maintenance priorities.

The general inspections occur every 2 years whereas principal inspections occur every 6 years. Principal inspections are thorough visual examinations of all parts of bridges, reporting all conditions and noting all defects. Defect severity is reported on a 1-to-5 scale, and defect extent on an A-to-E scale. These condition ratings are used in SMIS to generate the performance indicator for visual condition.

Special inspections, often involving material sampling or NDT applications, occur as needed. Inspections for HA’s (Highway Agency) 10,000 bridges are performed by consulting engineers. Inspections for the 100,000 bridges controlled by local roads agencies are performed by local agency staff or consultants.

The inspections of highways and main roads in England (Highways England), Scotland (Transport Scot-land), Wales (Llywodraeth Cymru Welsh Government), Ireland of North (Department for Infrastructure Northern Ireland) (Highway England et al., 2007) are governed by the standard BD 63/17, which was released in 2017. The document defines five types of inspections for motorway structures;

- (1) security inspection performed on easily accessible elements weekly or monthly depending on the structure by trained personnel,
- (2) general inspection performed every 2 years on visible elements,
- (3) principal inspection carried out in short or long periods (not more than 12 years) on visible elements,
- (4) special inspection on specific elements by visual inspection or measurements (tests),
- (5) inspection for assessment programmed to obtain necessary information and con-ducted generally at the same time with a principal inspection. Underwater inspection is a sort of examination that looks at portions of the construction that are below the water's surface. When the specific qualities of the structure are recognized by general, main, or safety inspections, special inspections are performed. All inspections must be carried out by engineers or trained individuals.

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A2-17 United States of America

The National Bridge Inspection Standards (NBIS 2009) provide the standards for inspecting and evaluating all highway bridges in the United States. The overall condition grade is awarded for three key components: deck, superstructure, and foundation, which are further separated into many elements, according to the American Association of State Highway and Transportation Officials (AASHTO) guideline for Condition Evaluation of Bridges.

There are eight different types of bridge inspections in the United States (Hsien-Ke Liao, 2017):

- **Initial** : first inspection of a bridge as it becomes a part of the bridge inventory to determine baseline structural conditions
- **Routine** : regularly scheduled inspection consisting of observations and/or measurements needed to determine the physical and functional condition of the bridge
- **Damage** : unscheduled inspection to assess structural damage resulting from environmental factors or human actions
- **In-depth** : a close-up inspection which investigates deficiencies that were not detected during routine inspection
- **Special** : an inspection scheduled at the discretion of the bridge owner, used to monitor a particular known defect or suspected deficiency
- **Underwater** : inspection of the underwater portion of a bridge substructure and the surrounding channel
- **Hands-on** : inspection within arm's length of the component; inspection uses visual techniques that may be supplemented by NDT
- **Fracture Critical Member** : a hands-on inspection of a fracture-critical member of component that may include visual and other non-destructive evaluation

The population of bridge inspections, inspection intervals, inspection techniques, inspection staff, and inspection reporting are all covered by federal rules. The Code of Federal Regulations is the primary source of federal requirements (Government, 2004).

The mechanism used in the United States for grading values during inspection is highly subjective. The inspector goes to the site and inspects each component of the bridge before assigning a score to the entire structure ranging from 0 to 9 according to the NBI condition rating system (Ryan T., 2012).

- **Rating 0 :** <u>failed condition</u> – out of service
- **Rating 1 :** <u>imminent failure condition</u> – major deterioration or section loss present in critical structural component, or obvious vertical or horizontal movement affecting structure stability
- **Rating 2 :** <u>critical condition</u> – advanced deterioration of primary structural elements
- **Rating 3 :** <u>serious condition</u> – los od section, deterioration, spalling or scour have seriously affected primary structural elements
- **Rating 4 :** <u>poor condition</u> – advanced section loss, deterioration, spalling or scour
- **Rating 5 :** <u>fair condition</u> – all structural elements are sound but may have minor section loss, cracking, spalling of scour
- **Rating 6 :** <u>satisfactory condition</u> – structural elements show some minor deterioration
- **Rating 7 :** <u>good condition</u> – some minor problems
- **Rating 8 :** <u>very good condition</u> – no problems discovered
- **Rating 9 :** <u>excellent condition</u>
- **Rating N :** <u>non-applicable</u>

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The ratings indicate the severity of a condition, but they do not identify or quantify the degree of deterioration. NBI condition rating system given below As a result, this rating system has limited utility in identifying the need for repairs and rehabilitation (Hsien-Ke Liao, 2017).

Moreover, a descriptive condition rating in terms of ‘good/fair/poor/not applicable’ is given by the inspector for each element (waterproofing, painting, road surface etc.) of the component, based on the deficiencies found on the individual element (Hsien-Ke Liao, 2017):

- **poor condition** – structural capacity of element is affected by advanced deterioration, section loss, spalling, cracking or other deficiency
- **fair condition** – structural capacity of element is not affected by minor deterioration, spalling, cracking etc.
- **good condition** – element is limited to only minor problems

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A2-18 China

As one of the leader in the SHM sector, it seems to be relevant to highlight the current trends in China (Guang-Dong Zhou, 2020). Comparing China's bridges with bridges in other countries, these infrastructures in China have specific characteristics such as: large quantities, long span, diverse loading and complicated environments. These factors made the application of SHM technologies on bridges the most active branch in the SHM community in China. In fact, there is an emerging industry in the civil engineering community and the great demand drives the development of various commercial systems. Unfortunately, some constraints are still stopping this process: the improper sensor selection, unreasonable sampling frequencies and unstable data processing. To boost this system a complete standardization system to regulate the implementation is required.

In addition, a variety of advanced techniques and methods have been developed for BHM. For example, various sensors based on resistance, piezoelectric ceramic and fiber Bragg grating have been devised and tested on real bridges; many signal processing approaches originating from the Fourier transform, the wavelet transform and the Hilbert Huang transform have been proposed and applied to identify modal parameters and performance indices, and multivariate statistical models, Bayesian statistical models and extreme value analysis models have been developed to describe the statistical characteristics of load and response (YL, 2018), (Lam HF, 2018). Diversiform linear, nonlinear and learning models are used to describe the relationships between the structural inputs and outputs and to predict the structural behavior in the future (Azimi M, 2020). These technologies and methods make BHM more effective, reliable, low-cost and intelligent. As a result, over 165 bridges whose main spans exceed 300 m in China are equipped with long-term BHM systems for varying motives. Some selected cases where BHM systems have been employed to evaluate structural performance during their lifetime are listed in the following table:

No.	Bridge name	Bridge type	Main span (m)	Sensor installed
1	Runyang South Tangtze River Bridge	Suspension	1490	Aznemometers, temperature sensors, strain sensors; accelerometers, global positioning systems.
2	Jiangyin Bridge	Suspension	1385	Anemometers, temperature sensors, strain gauges, accelerometers, displacements transducers, global positioning systems, elasto-magnetic sensors, optic fiber sensors, total stations.
3	Tsing Ma Bridge	Suspension	1377	Anemometers, temperature sensors, strain sensors, accelerometers, displacements transducers, global positioning systems, weigh-in-motion systems, level sensors, video cameras.
4	Ma'anshan Yangtze River Bridge	Suspension	1080	Anemometers, temperature sensors, hygrometers, global positioning systems, tiltmeters, strain sensors, accelerometers, displacement transducers.
5	Sutong Yangtze River Bridge	Cable-stayed	1088	Anemometers, temperature sensors, strain sensors, accelerometers, displacements transducers, global positioning systems, weigh-in-motion systems, corrosion sensors, elasto-magnetic sensors, optic fiber sensors, tiltmeters, hygrometers, video cameras.
6	Stonecutters Bridge	Cable-stayed	1018	Anemometers, temperature sensors, strain sensors, accelerometers, displacements transducers, global positioning systems, weigh-in-motion systems, corrosion sensors, elasto-magnetic sensors, tiltmeters,

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				barometers, hygrometers, pluviometers, video cameras.
7	Tongling Rail-cum-Road Changjiang River Bridge	Cable-stayed	630	Anemometers, temperature sensors, hygrometers, radar velocimeters, seismometer, global positioning systems, tiltmeters, displacement transducers, flexometers, elasto-magnetic sensors, accelerometers, strain sensors, video cameras.
8	2nd Nanjing Yangtze River Bridge	Cable-stayed	628	Anemometers, temperature sensors, strain sensors, accelerometers, weight-in-motion systems, elasto-magnetic sensors, total stations, hygrometers.
9	Chaotianmen Yangtze River Bridge	Arch	552	Anemometers, strain sensors, total stations, elasto-magnetic sensors, accelerometers.
10	Dashengguan Yangtze Bridge	Arch	336	Temperature sensors, hygrometers, strain sensors, anemometers, accelerometers, displacement transducers, video cameras, flexometer, radar velocimeters.

Table A2. 3 - BHM systems for evaluating structural performance (Guang-Dong Zhou, 2020))

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Annex 3 Statistics of trends and challenges based on CoP responses to IM-SAFE questionnaire *

A3-1 Trend 1: Condition-based inspection instead of Time Inspection

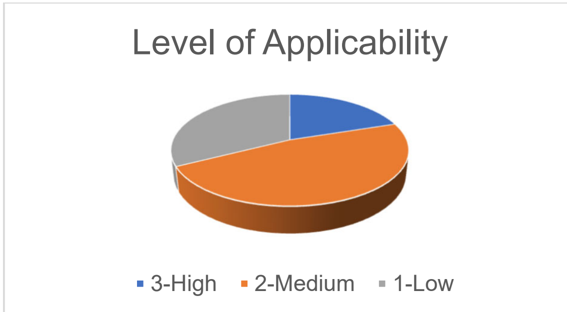

Figure A3. 1 - Most voted Level of Applicability of Condition-based inspection instead of Time Inspection trend

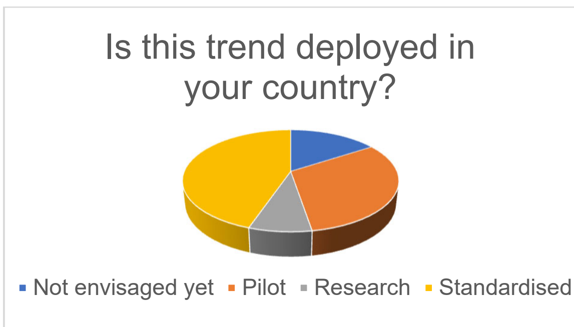

Figure A3. 2 - Most voted Level of Deployment of the Condition-based inspection instead of Time Inspection trend

Country	Level of Deployment
Austria	Research
Finland	Standardised
Germany	Pilot
Italy	Standardised
Netherlands	Standardised
Norway	Standardised
Spain	Pilot
Switzerland	Pilot

Table A3. 1 - Most voted Level of Deployment of the Condition-based inspection instead of Time Inspection trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Adjustment of budget
- Lack of standardization or regulations
- Lack of data. Not monitoring of the infrastructures
- Lack of personnel qualified
- Difficult to quantify the return over the investment

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A3-2 Trend 2: Drones inspection

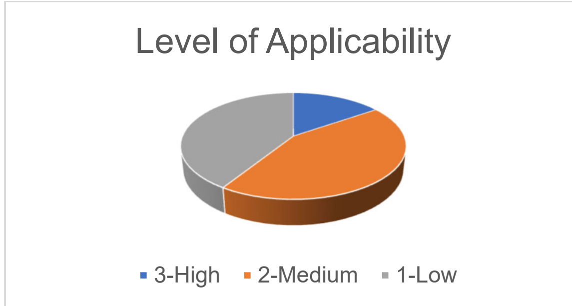

Figure A3. 3 - Most voted Level of Applicability of drones inspection trend

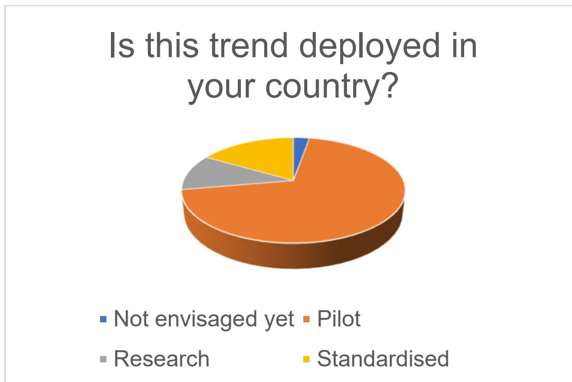

Figure A3 .4 - Most voted Level of Deployment of drones inspection trend

Country	Level of Deployment
Austria	Pilot
Bulgaria	Pilot
Finland	Pilot
Germany	Pilot
Italy	Pilot
Netherlands	Standardised
Norway	Standardised
Spain	Pilot
Switzerland	Research

Table A3-2: Most voted Level of Deployment of drones inspection trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Costs
- Lack of standardization or regulations
- Training of the personnel
- Sites requirements: not close to the airport
- Security measures
- Lack of quality requirements
- Reliability of the evaluation algorithms

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A3-3 Trend 3: Laser scanning

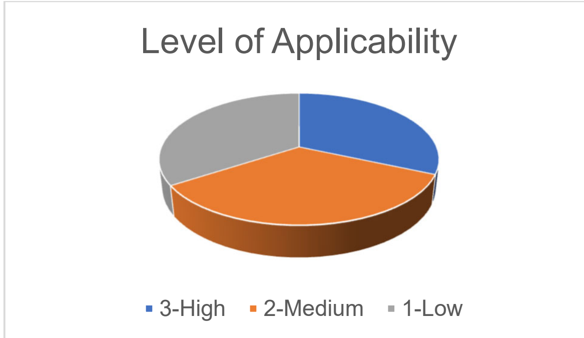

Figure A3. 5 - Most voted Level of Applicability of laser scanning trend

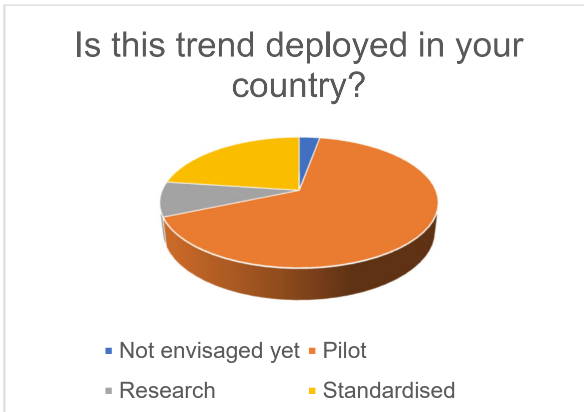

Figure A3. 6 - Most voted Level of Deployment of laser scanning trend

Country	Level of Deployment
Austria	Standardised/Pilot
Bulgaria	Pilot
Finland	Pilot
Germany	Pilot
Italy	Pilot
Netherlands	Standardised
Norway	Pilot
Spain	Pilot
Switzerland	Pilot

Table A3. 3 - Most voted Level of Deployment of laser scanning trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Intregration with other systems
- Mainly use for long-term infrastructure monitoring
- Cost
- It is the closest technology to standardization but not yet

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A3-4 Trend 4: Satellites

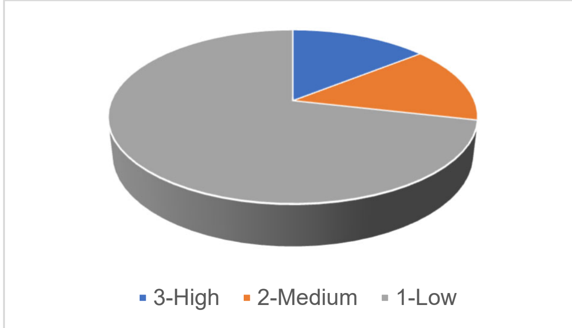

Figure A3. 7 - Most voted Level of Applicability of satellites trend

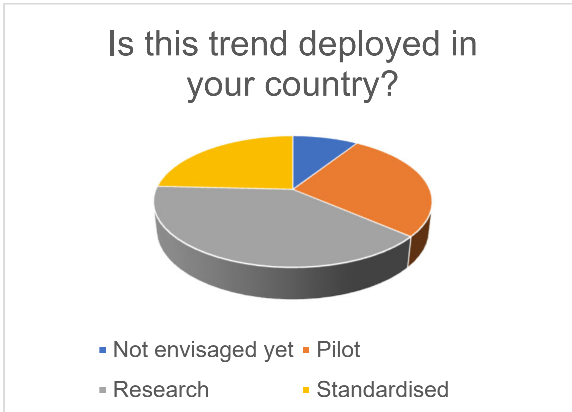

Figure A3. 8 - Most voted Level of Deployment of satellites trend

Country	Level of Deployment
Austria	Research
Finland	Not envisaged yet
Germany	Pilot
Italy	Research
Netherlands	Pilot
Spain	Research
Switzerland	Pilot

Table A3. 4 - Most voted Level of Deployment of satellites trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Visibility in the urban areas
- Immature technology
- High cost
- Lack of knowledge

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A3-5 Trend 5: Data collection: Sensor monitoring

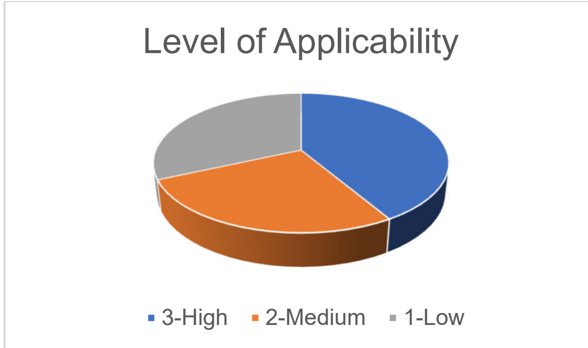

Figure A3. 9 - Most voted Level of Applicability of sensor monitoring trend

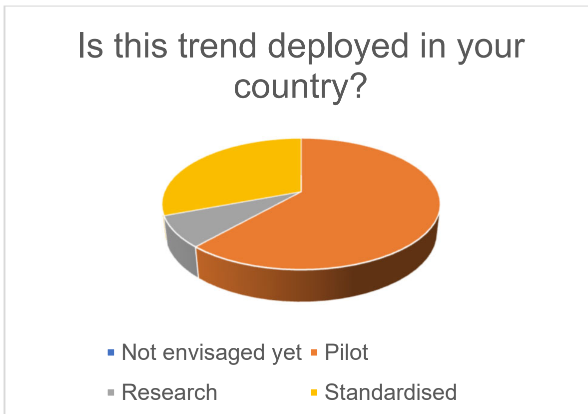

Figure A3. 10 - Most voted Level of Deployment of sensor monitoring trend

Country	Level of Deployment
Austria	Standardised/Pilot
Finland	Standardised
Germany	Pilot
Italy	Standardised
Netherlands	Pilot
Norway	Pilot
Spain	Pilot
Switzerland	Pilot

Table A3. 5 - Most voted Level of Deployment of sensor monitoring trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Quality of requirements for health monitoring
- Lack of standardisation
- Cost
- Lack of software to help processing and storing data

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A3-6 Trend 6: Cathodic protection to prevent corrosion of reinforcement in concrete

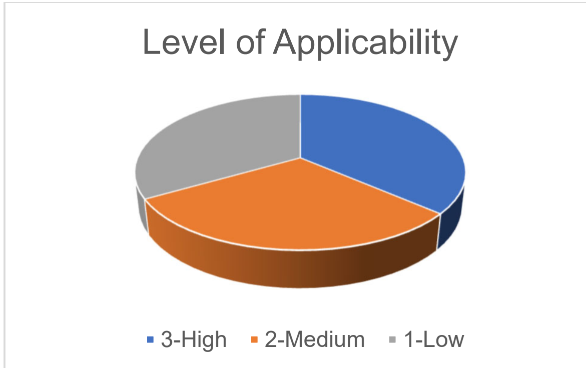

Figure A3. 11 - Most voted Level of Applicability of cathodic protection trend

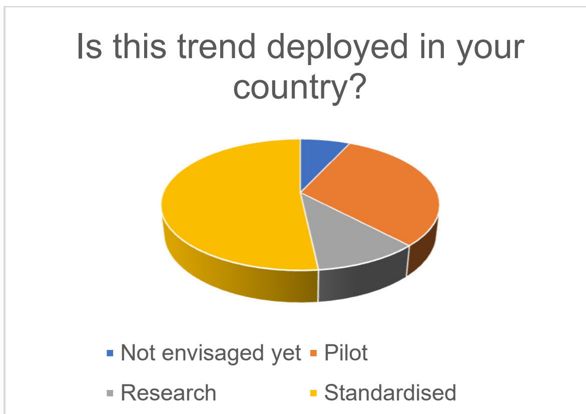

Figure A3. 12 - Most voted Level of Deployment of cathodic protection trend

Country	Level of Deployment
Austria	Standardised/Pilot
Bulgaria	Not envisaged yet
Finland	Pilot
Germany	Standardised
Italy	Not envisaged yet
Netherlands	Standardised
Norway	Standardised
Spain	Standardised

Table A3. 6 - Most voted Level of Deployment of cathodic protection trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Maintenance organizations are often not equipped for active maintenance
- Not suitable for many situations
- Cost

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A3-7 Trend 7: RCM (Reliability-centred maintenance)

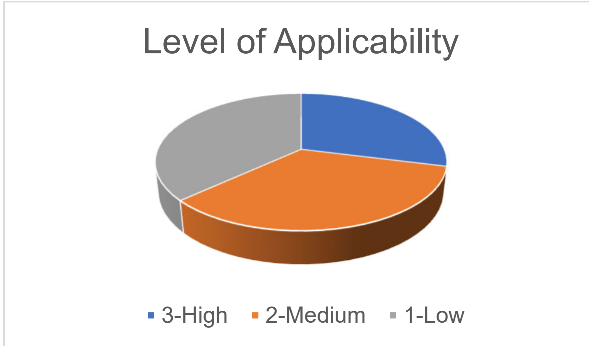

Figure A3. 13 - Most voted Level of Applicability of RCM trend

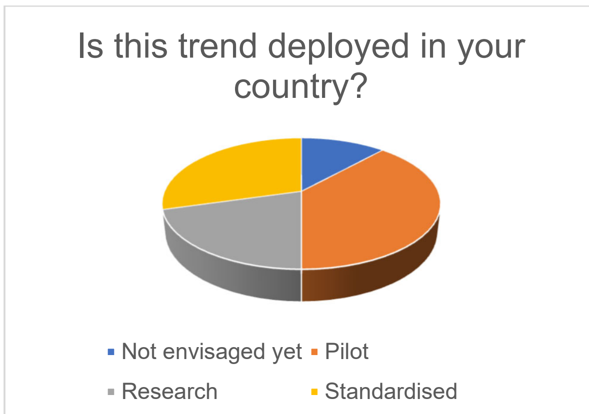

Figure A3. 14 -Most voted Level of Deployment of RCM trend

Country	Level of Deployment
Austria	Standardised
Bulgaria	Not envisaged yet
Finland	Pilot
Germany	Research/Pilot
Italy	Pilot/Research
Netherlands	Research
Norway	Pilot
Spain	Pilot
Switzerland	Pilot

Table A3. 7 - Most voted Level of Deployment of RCM trend by country

According to CoPs the main constraints to deploy this trend:

- Lack of standardisation
- Lack of resources
- Lack of knowledge of how to make transition of RCM in machinery to RCM on load-bearing

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A3-8 Trend 7: BIM

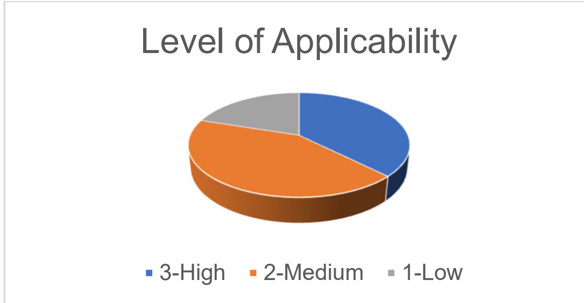

Figure A3. 15 - Most voted Level of Applicability of BIM trend

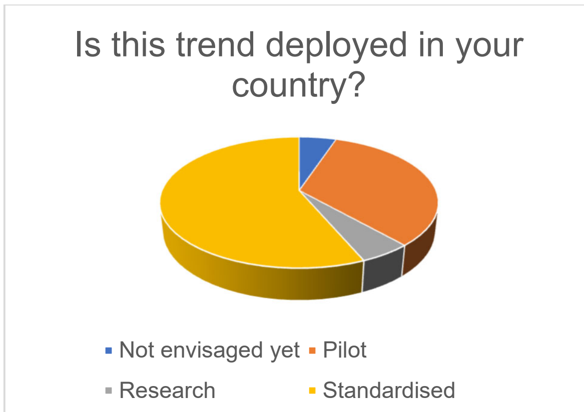

Figure A3. 16 - Most voted Level of Deployment of BIM trend

Country	Level of Deployment
Austria	Standardised/Pilot
Bulgaria	Research
Finland	Standardised
Germany	Standardised
Italy	Standardised
Netherlands	Standardised
Norway	Standardised
Spain	Standardised
Switzerland	Pilot

Table A3. 8 - Most voted Level of Deployment of BIM trend by country

According to the CoPs, the main constraints to deploy this trend are:

- Lack of knowledge
- Lack of training by the users

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A3-9 Trend 9: Data Management systems

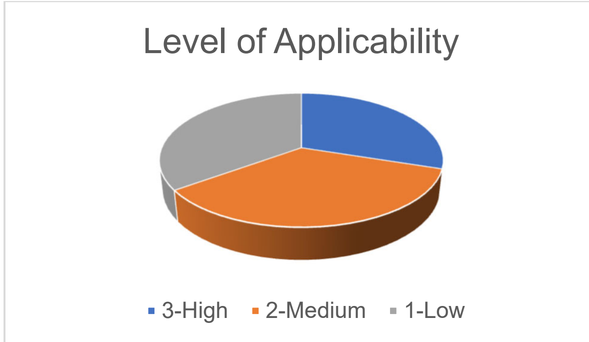

Figure A3. 17 - Most voted Level of Applicability of data management system trend

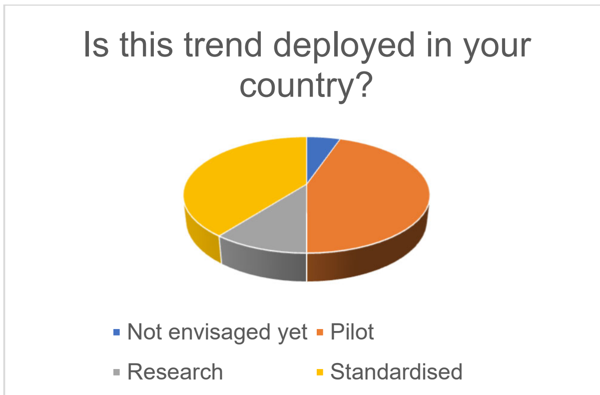

Figure A3. 18 - Most voted Level of Deployment of Data Management System trend

Country	Level of Deployment
Austria	Pilot
Bulgaria	Standardised
Finland	Standardised
Germany	Pilot/Standardised
Italy	Pilot
Netherlands	Standardised
Norway	Standardised
Spain	Pilot/Standardised
Switzerland	Pilot

Table A3. 9 - Most voted Level of Deployment of data management system trend by country

According to the CoPs, the main constraints to deploy this trend are:

- The Data Management system are not necessarily good and/or complete
- Ability to use by technicians
- Lack of data, multiple data systems. Only one system to integrate data is required
- The level of applicability of the system is set to medium

* If in any of the tables any of the countries is missing it is because there is not a clear picture of the applicability of the trend in that country according to the stakeholders that have completed the questionnaires provided to CoP by the IM-SAFE WP1.

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Annex 4 List of documents analysed

#	Key reports and standardisation documents	Document type (Standards, Research papers, Other reports)	Insfrastructure type
1	EU, CEDR, 2017, TEN-T performance report	Other reports	general
2	EU, EC DG GROW, 2012, M/515 EN: Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes	Other reports	bridge
3	EU, EC DG GROW, 2019, Discussion paper on 'state of infrastructure maintenance'	Other reports	general
4	EU, EC DG MOVE, 2019, Transport in the European Union Current Trends and Issues	Other reports	general
5	EU, ECTP, 2017, Position paper on 'maintenance and upgrading of existing transport infrastructures'	Other reports	general
6	EU, JRC, 2015, New European technical rules for the assessment and retrofitting of existing structures	Other reports	general
7	EU, JRC, 2016, Elaboration of maps for climatic and seismic actions for structural design with the Eurocodes	Other reports	general
8	EU, JRC, 2019, Research and innovation in bridge maintenance, inspection and monitoring: A European perspective based on the Transport Research and Innovation Monitoring and Information System (TRIMIS)	Other reports	general
10	EU, JRC, 2019, Standardisation needs for the design of underground structures	Other reports	tunnel
11	EU, JRC, 2019, State of harmonised use of the Eurocodes	Other reports	general

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12	EU, JRC, 2019, The implementation of the Eurocodes in the National Regulatory Framework	Other reports	general
13	EU, REFINET, 2017, Best practices in design, construction and maintenance of transport infrastructures	Other reports	general
17	International, fib, bulletin 22. “Monitoring and safety evaluations of existing concrete structures”.	Other reports	general
18	International, fib, bulletin 80. “Partial factor methods for existing concrete structures”.	Other reports	general
19	International, PIARC, 2016, Estimation of load carrying capacity of bridges based on damage and deficiency	Other reports	bridge
20	International, SAMCO, 2006, F08a –Guideline for the Assessment of Existing Structures and F08b - Guideline for Structural Health Monitoring	Other reports	general
21	ISO 13822:2010. Bases for design of structures - assessment of existing structures.	Standards	general
22	ISO 13824:2020. Bases for design of structures - General principles on risk assessment of systems involving structures.	Standards	general
23	ISO 14963:2003 Mechanical vibration and shock - Guidelines for dynamic tests and investigations on bridges and viaducts.	Standards	general
24	ISO 16587:2004 Mechanical vibration and shock - Performance parameters for condition monitoring of structures.	Standards	general
25	National, Austria, 2011, RVS 13.03.11. Checking and Assessment of Bridges and Tunnels, Road Bridges	Standards	general
26	National, Austria, 2012, Report: RVS13.03.01. Checking and Assessment of Bridges and Tunnels, Monitoring of Bridges and other Engineering Structures	Standards	general
27	National, Austria, 2017, RVS 13.05.11. Calculation of Life-Cycle-Costs for Bridges	Other reports	bridge

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28	National, Austria, 2019, Inspection and risk monitoring with high performance drones (UAS / UAV)	Other reports	general
29	National, Canada, 2001, Guidelines for Structural Health Monitoring - Design Manual No. 2	Standards	general
30	National, China, 2018, New Chinese Structural Health Monitoring Codes	Standards	general
31	National, Germany, 2013, Bauwerksprüfung nach DIN 1076	Standards	general
32	Bedeutung, Organisation, Kosten	Other reports	general
33	National, Italy, 2016, UNI/TR 11634:2016. Linee guida per il monitoraggio strutturale	Standards	general
34	National, Netherlands, NEN. Inventory of risk-based inspection process	Other reports	general
35	National, Norway, Overview of Norwegian bridges	Other reports	bridge
36	National, Russia, GOST R 53778-2010 - Building and Structures, Technical Inspections & Monitoring Regulations	Standards	general
37	National, UK, Codes regarding inspection and maintenance of bridges	Standards	general
38	National, US, Information system about bridges in the US	Other reports	general
39	JRC (2019): State of harmonised use of the Eurocodes, in support of the on-going activities of CEN/TC250 'Structural Eurocodes' to develop the second generation of the Eurocodes.	Other reports	general
40	JRC (2019): The implementation of the Eurocodes in the National Regulatory Framework	Other reports	general
41	JRC (2019): Research and innovation in bridge maintenance, inspection and monitoring	Other reports	bridge
42	JRC (2019): Standardisation needs for the design of underground structures	Standards	tunnel
43	EC DG GROW (2019): Discussion paper on 'state of infrastructure maintenance'	Other reports	bridge

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44	ECTP (2017): Position paper on ‘maintenance and upgrading of existing transport infrastructures’	Other reports	general
45	REFINET (2017): Report on ‘best practices in design, construction and maintenance of transport infrastructures’	Other reports	general
46	National, Norway, SVV V441 Bruinspeksjon (Bridge inspection)	Standards	general
47	UNI 10985 Vibrazioni su Ponti e Viadotti. Linee Guida per l'esecuzione di prove e rilievi dinamici	Standards	general
48	ISO 18649:2004 Mechanical vibration — Evaluation of measurement results from dynamic tests and investigations on bridges	Standards	bridge
49	UNI ISO 55000:2015 Gestione dei beni (asset management) - Panoramica, principi e terminologia	Standards	general
50	ISO 10137:2007: Bases for design of structures - Serviceability of buildings and walkways against vibrations	Standards	bridge
51	National, Italy, 2020, Ministero Infrastrutture e Trasporti, Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti	Standards	general
52	NAP 2-4-0.1 Norma Adif Plataforma. Inspección básica de túneles de ferrocarril	Standards	tunnel
53	NAP 2-4-0.1 Norma Adif Plataforma. Inspección principal de puentes de ferrocarril	Standards	bridge
54	National, Norway, NS 3424:2012 Tilstandsanalyse av byggverk, innhold og gjennomføring. (Condition survey of construction works, content and execution	Standards	general
55	DUTCH CROW-CUR 117: 2020 inspection and advise civil structures	Standards	general
56	NAP 2-4-1.1 Norma Adif Plataforma. Inspección principal de túneles	Standards	tunnel
57	NAP 2-4-0.0 Norma Adif Plataforma. Inspección básica de puentes	Standards	bridge
58	ITPF-05 Normativa de inspecciones en puentes de ferrocarril	Standards	tunnel

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59	F. Ubertinia, C. Gentile, A.Materazzi,, 'Automated modal identification in operational conditions and its application to bridges', Engineering Structures, Volume 46, January 2013, Pages 264-278	Research papers	bridge
60	A. Cigada, F. Lucà, M. Malavisi, G. Mancini, 'Structural Health Monitoring of a Damaged Operating Bridge: A Supervised Learning Case Study',Dynamics of Civil Structures, Volume 2, 2021	Research papers	bridge
61	NEN 2767-1, october 2017	Standards	general
62	NEN 2767-2, 2008	Standards	general
63	NEN 2767-4	Standards	general
64	NEN 3140+A3, operation of electrical installations - low voltage	Standards	general
65	CUR aanbeveling 102: Inspecteren en beoordelen van constructies met ASR	Standards	general
66	CROW-CUR Aanbeveling 124:2019: constructieve veiligheid bestaande bruggen en viaducten decentrale overheden	Standards	general
67	AustRoads Engineering guideline to bridge asset management	Other reports	bridge
68	Design Manual for Roads and Bridges CS 450 Inspection of highway structures	Standards	general
69	Design Manual for Roads and Bridges 451 Structural review and assessment of highway structures	Standards	general
70	Design Manual for Roads and Bridges 452 Inspection and records for road tunnel systems	Standards	tunnel
71	Design Manual for Roads and Bridges 453 The assessment of highway bridge supports	Standards	bridge
72	Design Manual for Roads and Bridges 454 Assessment of highway bridges and structures	Standards	bridge
73	Design Manual for Roads and Bridges 455 The assessment of concrete highway bridges and structures	Standards	bridge

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74	Design Manual for Roads and Bridges 456 The assessment of steel highway bridges and structures	Standards	bridge
75	Design Manual for Roads and Bridges 457 The assessment of composite highway bridges and structures	Standards	bridge
76	AM-STR-06005-01 Inspection and repair of concrete road structures	Standards	other
77	AM-STR-06006-02 The assessment of the fatgue life of corroded_	Standards	other
78	Proposed AASHTO guides for bridge preservation actions	Other reports	bridge
79	Synthesis 353 - Inspection and Maintenance of bridge stay cable systems	Other reports	bridge
80	Estimation of load carrying capacity of bridges based on damage and deficiency	Other reports	bridge
81	ISO 16311-2 Maintenance and repair of concrete structures - Assessment of existing concrete structures	Standards	general
82	TDOK 2013:0267 Krav Bärighetsberäkning av broar	Standards	bridge
83	TDOK 2013:0273 Råd Bärighetsberäkning av broar	Standards	bridge
84	TRVINFRA-00213 Inspektion av bro och övriga byggnadsverk, krav med rådstext	Standards	bridge
85	TRVINFRA-00215 Inspektion av tunnel och bergkonstruktioner, krav med rådstext	Standards	tunnel
86	TRVINFRA-00228 Bro och broliknande konstruktion, brounderhåll, krav med rådstext	Standards	bridge
87	NS 3424:2012 Tilstandsanalyse av byggverk - innhold og gjennomføring (condition survey of construction works - content and execution)	Standards	other
88	R412 Bruklassifisering med vedlegg	Standards	bridge
89	V441 V1 Bruinspeksjon. Vedlegg 1. Eksempelsamling skadetyper	Standards	bridge

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90	V441 V2 Bruinspeksjon. Vedlegg 2. Metoder oppmålinger/materialundersøkelser	Standards	bridge
91	R411 Bruforvaltning riksveg	Standards	bridge
92	Eftersyn af bygværker including appendices Vejregler Eftersyn af bygværker including appendices	Standards	general
93	Reliability-based classification of the load carrying capacity of existing bridges Vejdirektoratet Denmark 2004	Standards	bridge
94	ISO 4866:2010 Mechanical vibration and shock — Vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures	Standards	general
95	ISO 10813-2 Vibration-generating machines — Guidance for selection — Part 2 - Equipment for dynamic structural testing	Standards	general
96	ISO 16204-2012 Durability - Service life design of concrete structures	Standards	other
97	BIM Guidelines for Bridges	Other reports	bridge
98	Ciria - C764 Hidden Defects in Bridges – Guidance for Detection and Management	Other reports	bridge
99	EUROPEAN INVESTMENT BANK INVESTMENT REPORT: Building a smart and green Europe in the COVID-19 era	Other reports	general
100	Guidance on hidden defects in bridges in the UK and Ireland	Other reports	bridge
101	RI-ERH-ING: OSA Leitfaden Objektbezogene Schadensanalyse	Standards	general
102	Intelligente Brücke – Zuverlässigkeitsbasierte Bewertung von Brückenbauwerken unter Berücksichtigung von Inspektions- und Überwachungsergebnissen	Research papers	bridge

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103	Intelligente Brücke - Schädigungsrelevante Einwirkungen und Schädigungspotenziale von Brückenbauwerken aus Beton	Research papers	bridge
104	Intelligente Bauwerke - Prototyp zur Ermittlung der Schadens- und Zustandsentwicklung für Elemente des Brückenmodells	Research papers	bridge
105	Intelligente Brücke - Konzeption eines modular aufgebauten Brückenmodells und Systemanalyse	Research papers	bridge
106	Intelligente Brücke - Machbarkeitsstudie für ein System zur Informationsbereitstellung und ganzheitlichen Bewertung in Echtzeit für Brückenbauwerke	Research papers	bridge
107	D3.3 – Catalogue of technologies for multi-modal transport infrastructures	Other reports	general
108	Geometrical product specifications (GPS) Geometrical product specifications (GPS) — Surface texture: Areal — Part 600: Metrological characteristics for areal topography measuring methods	Standards	general
109	Buildings and civil engineering works Procedures for setting out, measurement and surveying — Vocabulary	Standards	general
110	Optics and optical instruments Field procedures for testing geodetic and surveying instruments — Part 9: Terrestrial laser scanners	Standards	general
111	IAP-11: Instrucción sobre las acciones a considerar en el proyecto de puentes de carretera	Standards	general
112	Documento básico de seguridad estructural	Standards	general
113	ISO 18649:2004 Mechanical vibration — Evaluation of measurement results from dynamic tests and investigations on bridges	Standards	bridge
114	ISO 14963:2003 Mechanical vibration and shock — Guidelines for dynamic tests and investigations on bridges and viaducts	Standards	bridge
115	ISO 16587:2004 Mechanical vibration and shock — Performance parameters for condition monitoring of structures	Standards	general
116	Structural Health monitoring Standars	Research papers	general

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117	UNE-EN 1330-10 Ensayos no destructivos Terminología, Términos utilizados en inspección visual	Standards	general
118	UNE-EN 1991-2 Eurocódigo 1: Acciones en estructuras, Parte 2: cargas de tráfico en puentes	Standards	bridge
119	EN 1992-2:2005 Eurocódigo 2: proyecto de estruturas de hormigón parte 2: Puentes de hormigón	Standards	bridge
120	UNE-EN 1993-2 Eurocódigo 3: Proyecto de estructuras de acero Parte 2: puentes	Standards	bridge
121	UNE-EN 1994-2 Eurocode 4: Proyecto de estructuras mixtas de acero y hormigón, parte 2: reglas generales y reglas para puentes	Standards	bridge
122	UNE-EN 1995-2 Eurocódigo 5: Proyecto de estrucuturas de madera, parte 2: Puentes	Standards	bridge
123	UNE-EN-ISO 16809 Ensayos no destructivos medición del espesor mediante ultrasonidos	Standards	general
124	UNE-EN-ISO 19650-1 Organización y digitalización de la información en obras de edificación e ingeniería cvil que utilizan BIM	Standards	general
125	UNE-EN-ISO 19650-2 Organización y digitalización de la información en obras de edificación e ingeniería cvil que utilizan BIM	Standards	general
126	UNE 178107-4 IN Guía para las infraestrucutras de ciudades inteligentes	Standards	general
127	UNE-EN IEC 61757:2018 Sensores de fibra óptica Parte 1: especificación genérica	Standards	general
128	UNE-EN IEC 63041-1:2018 Sensores piezoeléctricos Parte 1: Especificaciones generales	Standards	general
129	ORDEN CIRCULAR 2/2021 SOBRE LA PLATAFORMA DE MONITORIZACIÓN DE ESTRUCTURAS DE LA RED DE CARRETERAS DEL ESTADO	Standards	general
130	Guia de inspecciones básicas para las obras de paso de Ministerio de Fomento	Standards	bridge

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131	Guia de inventario de obras de paso del Ministerio de Fomento	Standards	bridge
132	Guia para la realizacion de inspecciones en obras de paso del Ministerio de Fomento	Standards	bridge
133	NS 1-1-1995 Obras de paso	Standards	bridge
134	NS 9-3-2007 Obras de fabrica	Standards	bridge
135	OC 27-2008 Guia de inspeccion de tuneles del MF	Standards	tunnel
136	RCE OC 33-2013 Manual de explotacion de tuneles del MF	Standards	tunnel
137	RD 635-2006 Requisitios minimos de seguridad en tuneles	Standards	tunnel
138	RD 635-2006 Modificado	Standards	
139	RES 30-5-12 Analisis de riesgo en tuneles	Standards	tunnel
140	EU, REFINET, 2017, Catalogue of technologies for multi-modal transport infrastructures	Other reports	other
141	Utah: Monitoring Strain on Precast Bridge Deck https://s.campbellsci.com/documents/us/case-studies/utah-strain-bridge-deck.pdf	Other reports	bridge
142	https://www.campbellsci.com/case-studies	Other reports	
143	Real Time GNSS bridge monitoring http://w3.leica-geosystems.com/media/new/product_solution/Reporter_61_GNSS_bridge-Monitoring_EN.pdf	Other reports	bridge
144	James FIsher Testing Services to deliver advanced structural health monitoring upgrades for large bridge project in France https://www.jftesting-services.com/media/news-and-press-releases/jfts-deliver-advanced-structural-health-monitoring-upgrades-large-bridge-project-france/	Other reports	bridge
145	Bridge Instrumentation and Structural Health Monitoring https://smartec.ch/wp-content/uploads/sites/2/2017/01/E-APN_BRIDGES-_170216_01.pdf	Other reports	bridge

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146	https://roctest.com/wp-content/uploads/2017/01/Bridge-Ref_1911-ROCTEST.pdf	Other reports	
147	Machine Condition Monitoring on Chanban-Delmas Bridge https://dewesoft.com/case-studies/bridge-machine-condition-monitoring	Other reports	
148	Bridge Instrumentation Structural Health Monitoring https://www.spiedigitallibrary.org/conference-proceedings-of-spie/5050/0000/Health-monitoring-of-the-Saint-Jean-bridge-of-Bordeaux-France/10.1117/12.484244.short?SSO=1	Other reports	bridge
149	Hydraulics and bridges: A French case study of monitoring of a bridge affected by scour https://www.researchgate.net/publication/342708722_Hydraulics_and_bridges_A_French_case_study_of_monitoring_of_a_bridge_affected_by_scour	Research papers	bridge
150	Lessons Learned in Structural Health Monitoring of Bridges Using Advanced Sensor Technology http://www.diva-portal.org/smash/get/diva2:456855/FULLTEXT01.pdf	Research papers	bridge
151	Health monitoring and Evaluation of Long-Span Bridges Based on Sensing and Data Analysis: A Survey https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5375889/	Research papers	bridge
152	High frequency Deflection Monitoring of Bridges by GPS https://www.researchgate.net/publication/228856256_High_Frequency_Deflection_Monitoring_of_Bridges_by_GPS	Research papers	bridge
153	https://link.springer.com/chapter/10.1007/978-3-642-59742-8_58	Other reports	
154	Mid-span defelction monitoring of Humber Bridge using cameras https://veswordpresscom.wordpress.com/2015/09/23/mid-span-deflection-monitoring-of-humber-bridge-using-cameras-2/comment-page-1/#comments	Other reports	bridge
155	Case Study: Structural monitoring Humber Bridge Kingston upon Hull, England https://www.geosig.com/Structural-Monitoring---Humber-Bridge--England-pg99.aspx	Other reports	bridge

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156	https://www.researchgate.net/publication/245533898_Wireless_structural_health_monitoring_at_the_Humber_Bridge_UK	Other reports	
157	Experimental monitoring of the Humber Bridge using GPS https://www.researchgate.net/publication/245411861_Experimental_monitoring_of_the_Humber_Bridge_using_GPS	Research papers	bridge
158	Structural Health Monitoring Systems http://www.shms.dk/COWI_ISBN-87-91044-04-9.pdf	Research papers	general
159	https://www.sciencedirect.com/science/article/abs/pii/0141029693900548	Other reports	bridge
160	Structural Health Monitoring of Long-Span Suspension Bridges (Book https://www.routledge.com/Structural-Health-Monitoring-of-Long-Span-Suspension-Bridges/Xu-Xia/p/book/9781138075634	Other reports	bridge
161	https://research.utwente.nl/en/publications/data-driven-damage-detection-for-bridges-through-vibration-struct	Other reports	bridge
162	https://www.diva-portal.org/smash/get/diva2:458107/FULLTEXT01.pdf#page35	Other reports	bridge
163	IoT Enabled 24x7 Bridge Structure Health Monitoring https://www.signaguard.com/case-studies-in-bridge-health-monitoring/	Other reports	bridge
164	https://onlinelibrary.wiley.com/doi/abs/10.1002/stc.1979	Other reports	bridge
165	https://www.degruyter.com/document/doi/10.1515/jag-2013-0020/html	Other reports	bridge
166	A Large Scale SHM System: A Case Study on Pre-stressed Bridge and Cloud Architecture https://link.springer.com/chapter/10.1007/978-3-030-12115-0_10	Research papers	bridge
167	Structural Health Monitoring of a Damaged Operating Bridge: A Supervised Learning Case Study https://link.springer.com/chapter/10.1007/978-3-030-47634-2_19	Research papers	bridge
168	Structural Health Monitoring Case Study Review https://www.ripublication.com/ijcer17/ijcerv8n1_03.pdf	Research papers	general
169	Continuous monitoring of Chillon viaduct under environmental and operational variability conditions	Research papers	general

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	https://sites.tufts.edu/shmcasestudies/files/2020/06/SHMCaseStudy_Monitoring_of_Chillon_Viaduct_ETH.pdf		
170	https://sites.tufts.edu/shmcasestudies/category/bridge/	Other reports	bridge
171	https://www.researchgate.net/publication/291584378_Case_Studies_of_Structural_Health_Monitoring_of_Bridges	Other reports	bridge
172	Structural Health Monitoring of Bridges in Mexico - Case Studies https://www.researchgate.net/publication/335404304_Structural_Health_Monitoring_of_Bridges_in_Mexico_-Case_Studies	Research papers	bridge
173	Case Studies: Structural Health Monitoring for Real-Time Asset Managament of Small Bridges https://na.eventscloud.com/file_uploads/e2d0f915f1fc3738d89075dd911a8407_Structural_Health_Monitoring_for_Real-Time_Asset_Management_of_Small_Bridges_CSIRO_Peter_Runcie.pdf	Research papers	bridge
174	https://www.sciencedirect.com/science/article/abs/pii/S0141029618333054	Other reports	bridge
175	https://www.sciencedirect.com/science/article/abs/pii/S0141029618336563	Other reports	bridge
176	Structural Health Monitoring for Bridge Structures using Smart Sensors https://core.ac.uk/download/pdf/158301632.pdf	Research papers	bridge
177	https://link.springer.com/article/10.1007/s13349-015-0115-x	Other reports	bridge
178	Structural Health Monitoring (SHM) system implemented in Sorraia River https://www.researchgate.net/profile/Jose-Matos-13/publication/260943115_Structural_Health_Monitoring_SHM_system_implemented_in_Sorraia_River_Bridge/links/00b7d532b1f03798cd000000/Structural-Health-Monitoring-SHM-system-implemented-in-Sorraia-River-Bridge.pdf?origin=publication_detail	Research papers	bridge
179	C-ROADS - The platform of harmonised C-ITS deployment in Europe www.c-roads.eu	Other reports	other
180	5G advances to provide a platform to support auomotive sector www.5gcarmen.eu	Other reports	other

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181	ICT infrastructure to enable automation (up to L4)www.ict4cart.eu	Other reports	general
182	Automated Pavement Crack Segmentation Using U-Net-Based Convolutional Neural Network	Research papers	general
183	Concrete Crack Images for Classification : Deep learning for detecting cracks in concrete bridges	Research papers (online + dataset)	general
184	TACK PROJECT: TUNNEL AND BRIDGE AUTOMATIC CRACK MONITORING, isprs-archives-XLIII-B4-2020-741-2020	Research papers	general
185	DeepCrack Neurocomputing: A deep hierarchical feature learning architecture for crack segmentation	Research papers	general
186	https://www.researchgate.net/publication/350359479_Research_in_bridge_maintenance_safety_and_management_An_overview_and_outlook_for_Europe	Other reports	bridge
187	https://www.researchgate.net/publication/350369251_Inspection_of_roadway_bridges_A_comparison_at_the_European_level	Other reports	bridge
188	Comparison of Bridge Inspection Methodologies and Evaluation Criteria in Taiwan and Foreign practices https://www.researchgate.net/publication/319112076_Comparison_of_Bridge_Inspection_Methodologies_and_Evaluation_Criteria_in_Taiwan_and_Foreign_Practices	Research papers	bridge
189	Assessment of Bridge Management System in Iran https://www.sciencedirect.com/science/article/pii/S1877705813004062	Research papers	bridge
190	Bridge Preservation and maintenance in Europe and South Africa https://www.researchgate.net/publication/298792725_Bridge_Preservation_and_Maintenance_in_Europe_and_South_Africa	Other reports	bridge
191	RI-EBW-PRÜF - 2017 Richtlinie zur einheitlichen Erfassung, Bewertung, Aufzeichnung und Auswertung von Ergebnissen der Bauwerksprüfungen nach DIN 1076	Standards	other

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192	RPE-ING - 2020 Richtlinien für die strategische Planung von Erhaltungsmaßnahmen an Ingenieurbauwerken	Standards	other
193	ASB-ING - 2013 Anweisung Straßeninformationsdatenbank Segment Bauwerksdaten	Standards	other
194	DIN 1076 - 1999 Ingenieurbauwerke im Zuge von Straßen und Wegen Überwachung und Prüfung	Standards	other
195	RI-WI-BRÜ Richtlinie zur Durchführung von Wirtschaftlichkeitsuntersuchungen im Rahmen von Instandsetzungs-/ Erneuerungsmaßnahmen bei Straßenbrücken	Standards	bridge

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