DIGITAL BRIDGE MONITORING SYSTEMS - META STUDY

D.1.4.1 Meta study on findings from prior activities emphasizing needs and requirements of bridge owners

Project title: "Bridge monitoring using real-time data and digital twins for Central Europe"
Project acronym: BIM4CE
Partnership: 8 partners, 3 countries, 6 regions
Project duration: 36 months
Project webpage: https://www.interreg-central.eu/projects/bim4ce/

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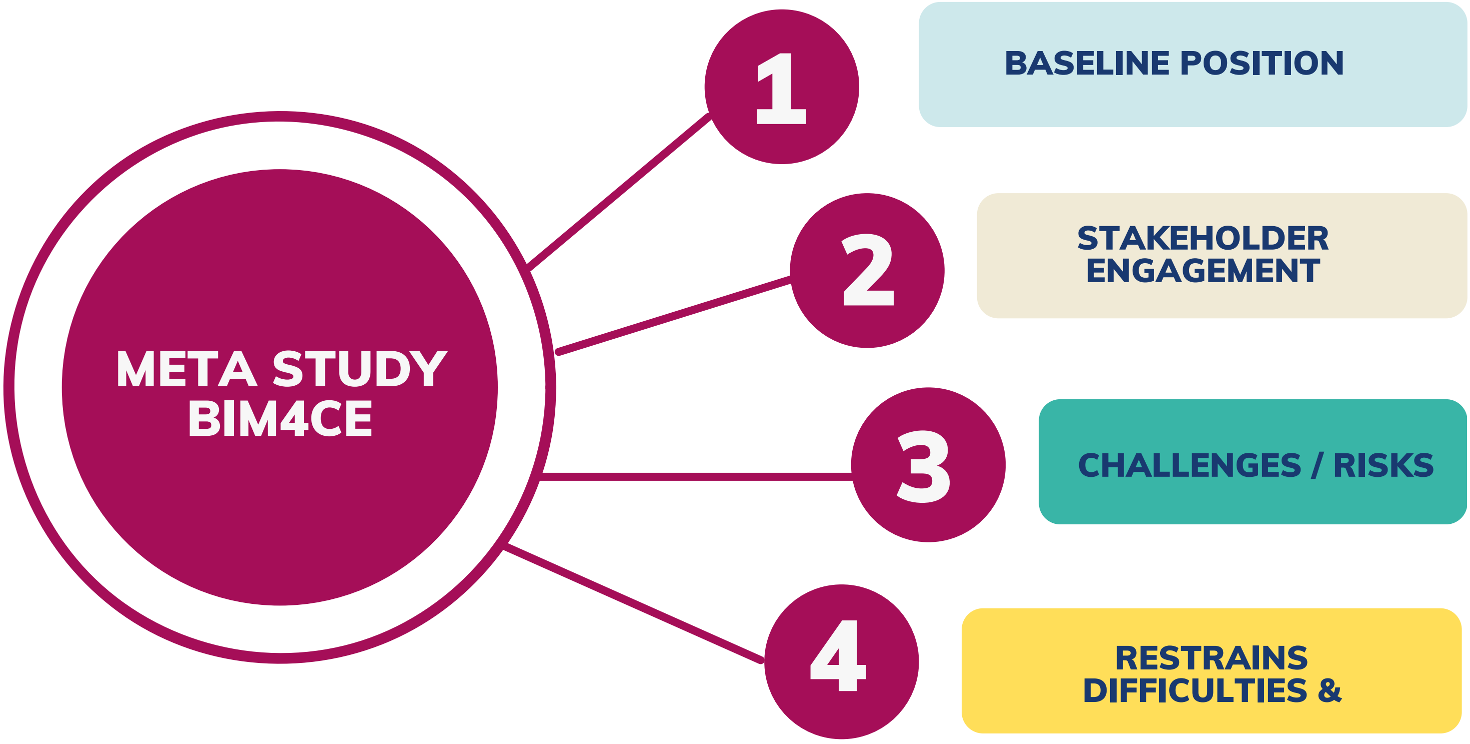
AIM OF THE META STUDY

The meta study synthesizes all information gathered in project activities such as report on existing bridge types, white paper on needs & requirements related to digital bridge monitoring systems, current state of bridge monitoring systems, risk matrix, conceptual framework for application of digital monitoring system, IoT, etc. . The aim is to derive possible functional approaches for a solution that meets identified requirements of bridge owners and operators. The document offers a comprehensive overview of (digital) bridge monitoring methods. Moreover, it includes information received from stakeholders in relevant fields (e.g. politics, science and industry) as well as clearly stated needs and requirements of bridge owners. The focal point of the study is the so called “Bridge Health Monitoring system” (BHM). Such systems assess the bridge's health and are recognized as one of the best ways to increase general safety, thus optimizing bridge operation and maintenance activities.



BASELINE POSITION

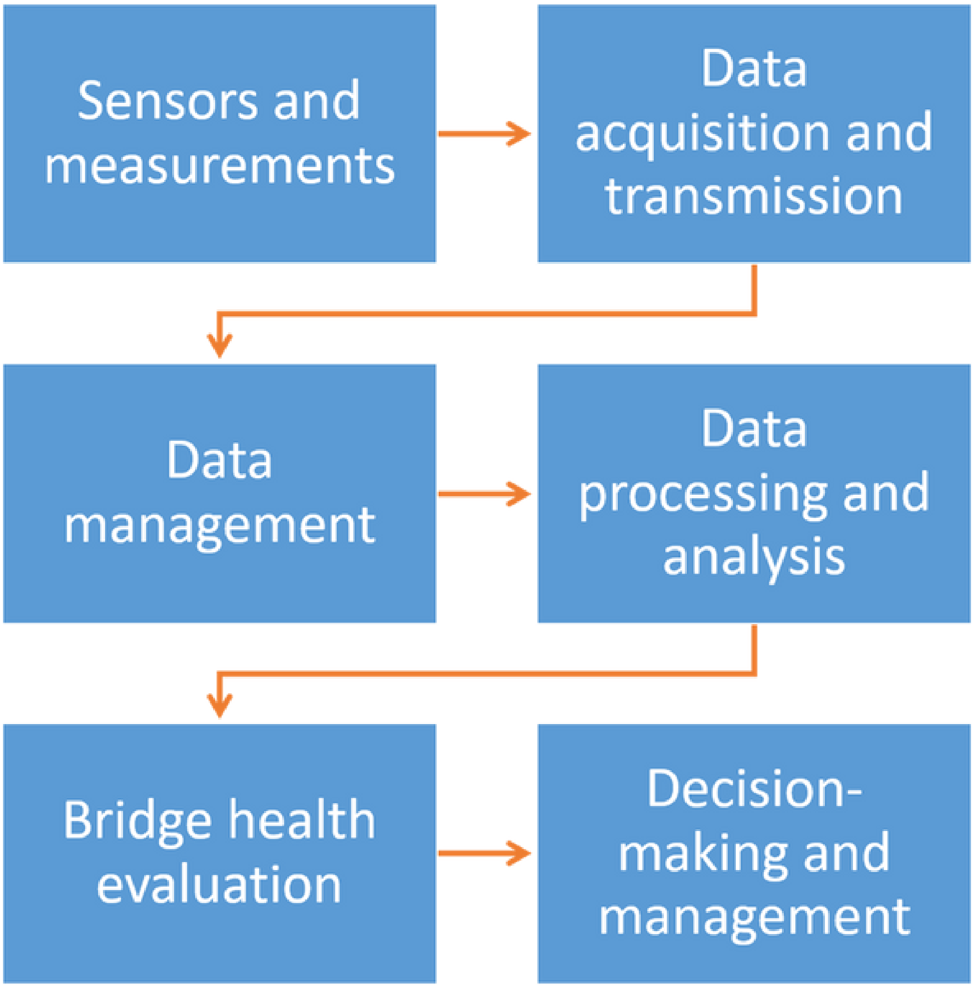
One of the main goals of the BIM4CE project is to design a long-term digital monitoring system for bridges in Central Europe. The long-term phase of the BHM system aims at assessing the loss of capacity of the bridge over time, as a consequence of the normal degradation of the structures. The purpose of the long-term monitoring is to guarantee serviceability, safety, sustainability of the bridge, and low operational cost. The development of modern information and communication system, signal processing technology, Internet, and structural analysis significantly advances the application and improvement of the BHM systems. Despite these advancements, there still exist big challenges, which need to be addressed in the future. The main goal of this study is to offer a comprehensive understanding of innovative pilot methods to be applied in digital monitoring systems for BHM (Bridge Health Monitoring) purposes.

The choice of pilot sites is based on the desirable characteristics reported in the following table:

Item	Description
Bridge types	Slab bridges
	Grider bridges
Material	Reinforced/Prestressed Concrete
Span length	Between 6 m and 40 m
Deck thickness	Up to 80 cm (slab bridge) Up to 250 cm (beam / deck combination)
Number of lanes	Up to four
Other parameters	No skew Smooth approach Road surface in a good condition

DIGITAL BRIDGE MONITORING SYSTEM

From the logical standpoint the BHM framework is composed of subsystems that function as following:



- **Sensors and measurements** are used to gather/ sense information of bridge's working environment as well as various other factors that affect the safety of the bridge (e.g. wind speed/direction, environmental temperature, humidity, traffic loads, vibrations, displacements, strains, etc;
- **Data acquisition and transmission:** the information acquired by sensors is sampled and transmitted;
- **Data management:** receiving and data storage of gathered information;
- **Data processing and analysis:** obtained data is processed, analyzed and transformed to an optimized form ready to be used for further elaboration;
- **Bridge Health evaluation** includes algorithms and methodologies for evaluation to assess the condition of the bridge;
- **Decision-making and analysis:** obtained data is utilized by bridge managers to make decisions regrading target bridges (e.g. maintenance, repair, strengthening or reconstruction.

MONITORING SYSTEM TYPES

Monitoring system types include **dynamic, static, and environmental monitoring systems.**

Types and positions of sensors based on types of monitoring systems are as following:

Monitoring System Type	Sensor Type	Position
Dynamic monitoring	Triaxle accelerometer on deck	Beam/Deck
	Triaxial accelerometer on pier or abutment	Pier/Abutment
	Strain sensors	Beam/Deck
Static monitoring	Biaxial inclinometer on deck	Beam/Deck
	Biaxial inclinometer on pier or abutment	Pier/Abutment
	Longitudinal displacement transducer	Support/Restraint device
	Transverse displacement transducer	Support/Restraint device
	Strain sensors	Beam/Deck/Pier/Abutment/Support Device
Environmental monitoring	Printable flexible temperature sensors	Beam/Deck/Pier
	Weather Station	Deck top surface/Top of abutment
	Printable Moisture sensors under the moisture insulation layer	Deck, under the moisture insulation layer
	Printable Pressure sensors based on piezoelectric effect or capacitive measurement	Deck

STAKEHOLDER ENGAGEMENT

Stakeholder involvement is important for several reasons. Specifically, stakeholder engagement can help to create sustainable change, facilitate information and make it possible to develop a specific approach or strategy. By satisfying the needs and interests of relevant stakeholders, we give importance to gained/ established project results. Stakeholder input helps to inform decisions and provides the support needed for long-term sustainability.
At the beginning of the project the partners devised a stakeholder list to not only get the end-users feedback but to pave the way for future pilot actions.
Thus, several stake holders have provided feedback (via project partners) on requirements and wishes in terms of digital bridge monitoring systems.

CESTEL:
1) Constantly data on exceptional transports including speeds, dynamic weight must be provided by the sensors;
2) Long-term statistical data on traffic is also required (e.g. number of heavy goods vehicles crossing a bridge/road section in a given period, how many were overloaded, by how much, etc.);
3) Structural parameters such as influence line, dynamic amplification factor, load distribution, information on strains, etc. bear significant importance.

<u>Solution:</u> pressure sensor foild of TU Dresden can be used to measure / gather all listed parameters.

TUD:
1) Pre-warning detection systems should be included to avoid maintenance at critical parts of infrastructure (e.g., important for logistics bridges with high day traffic load).
2) Condensation sensors to detect the condensation isolation layers on the bridges that used to protect the concrete slabs. The damage of such layer causes penetration of the water into the cracks of slabs and causes large damage during the water freezing.

<u>Solution:</u> Printable flexible condensation sensors underneath the moisture isolation layer can warn the bridge owner about the necessity of maintenance.

STAKEHOLDER ENGAGEMENT

Existing sensors on the market: RFID tags that are installed locally and can detect moisture at large amount and in specific locations.
Rusting sensors are also RFID and require the wiring around vulnerable metal parts.

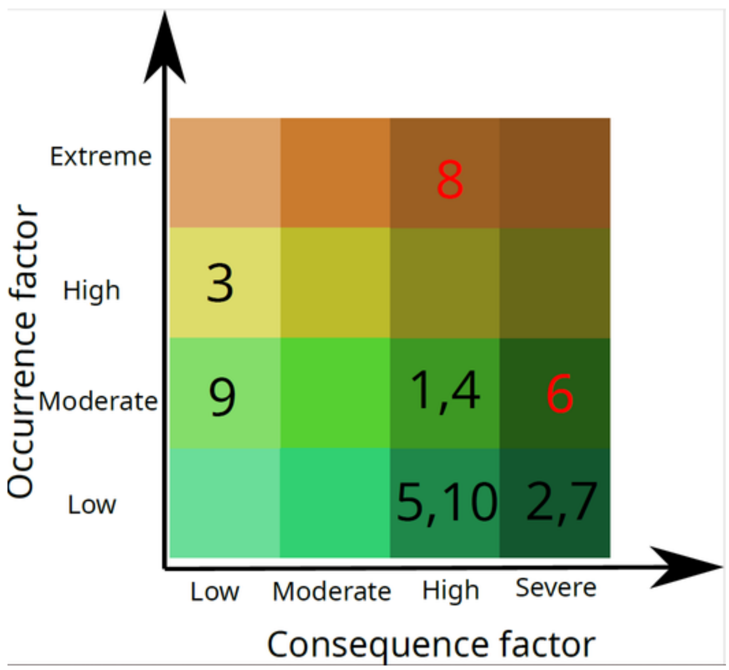
SITAF: Typically low levels of noticeable ice pellets, snow, or sleet surrounding black ice means that areas of the ice are often next to invisible to drivers or people walking on it. Thus, there is a risk of slippage and subsequent accident due to the unexpected loss of traction.

<u>Solution:</u> For this reason ice detector sensor for monitoring of black ice crystallization (Italian mountains) are an important monitoring feature.

RISKS ASSOCIATED WITH BRIDGES

The risks associated with the prestressed and reinforced concrete bridges are presented in the table below:

No.	Risk	Consequence
1	Cracks in prestressed	corrosion of beams
2	Corrosion of prestressing reinforcement	severe collapse of the prestressed girder bridge
3	Cracks in concrete (Caused by thermal expansion and shrinkage of concrete)	delamination of concrete and corrosion of reinforcement
4	Crack caused by loading	medium deck cracks, delamination of concrete, and corrosion of reinforcement
5	Medium deck cracks	defects in bridge construction
6	Malfunction of hydro isolation (leaking of water with salt during the winter)	severe corrosion of inner reinforcement and the bridge collapse
7	Spalling or delamination of concrete (effects of water, de-icing chemicals, and freeze cracking)	severe casualties to nearby people
8	Corrosion of attachments, screws, bolts, and railings	falling off the parts of the bridge on passing infrastructure units
9	Sensor connection malfunction, power supply blackout	Sensors or power supply must be replaced
10	Power supply malfunction (not isolated wiring of power supply, open source of high electricity voltage)	deadly casualty if they are located at the publicly accessible places



RISKS ASSOCIATED WITH BRIDGES

Elaboration of the risks matrix

- **Deck cracks** - small cracks in girder (steel beam) occur very often. Thus, proper monitoring of such cracks is a crucial prevention method that halts the uncontrolled augmentation of said cracks, since (in most cases) the maintenance of such cracks is a very costly endeavor.

- **Medium deck cracks** - depending on the profoundness of cracks, these ruptures can cause defects in the construction of the bridge, resulting in repair(s) of the concrete bridge slab.

- **Spalling of abutments** – usually the part of a structure such as an arch or a bridge (abutments) that directly receives thrust or pressure, may deteriorate from the effects of water, deicing chemicals, freeze cracking, thus early prevention of such occurrences might avoid severe damage.

- **Buckling of girder flange** - the buckling of a girder flange occurs on bridges with metal girders when the maximum load of the bridge is not fulfilled. Although, a rare phenomenon, the related repair costs are very high.

- **Corrosion of metal parts** - the gradual deterioration of parts that are made out of metal might lead to the severe collapse of prestressed girder bridges, thus requiring a full reconstruction of the bridge.

- **Absence of (suitable) power supply** - constant measurement are needed (e.g. each 30 seconds), thus batteries deplete very fast resulting in very short battery life (1-2 days), which, in turn, causes difficulties in changing batteries on bridges with limited access.

RESTRAINS & DIFFICULTIES

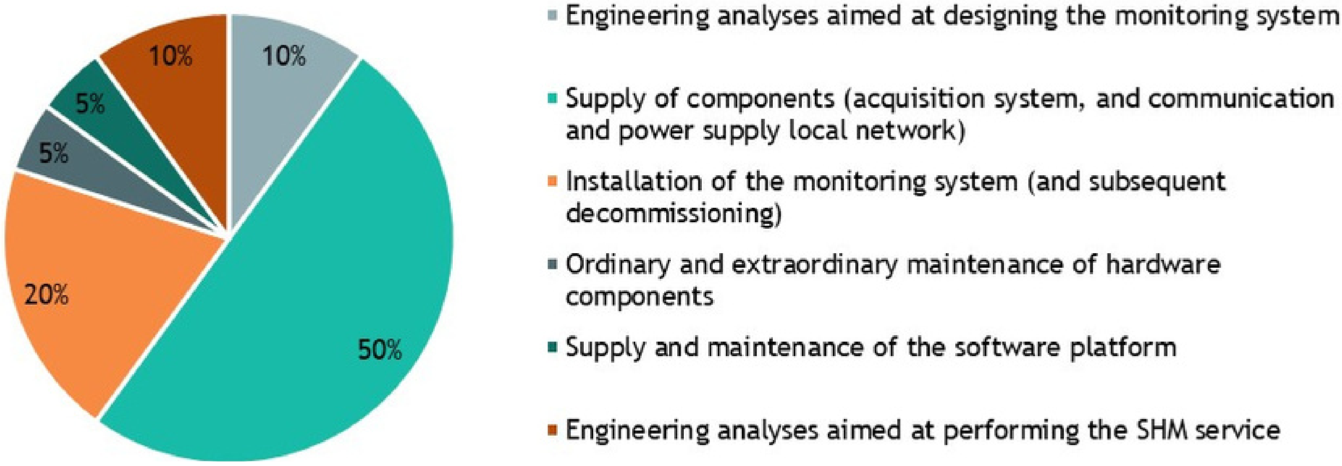
Elaboration of restrains & difficulties and listing of possiblie solutions

- **Installation Difficulties:**

Flexible PET foils do not stick to the concrete. This, in turn, makes it difficult to use gauge sensors to measure the bridge stretching or cracks.

- **Budget restrains in connection to bridge owners:**

The total cost of a bridge monitoring system is significantly influenced by these **3 factors**: type of the implemented monitoring system, type and geometry of the bridge structure and the morphology of the place.
Costs of the entire monitoring system are presented in the below graph:



The cost of a complete monitoring system (24 sensors) >>> € 20,000 per span, include:

- € 10,000 (50 %) per span for the sensors;
- € 6,000 (30 %) per span for the acquisition and analysis devices, including the CPU;
- € 2,000 (10 %) per span for the sensor wiring;
- € 2,000 (10 %) per span for the local communication and power supply network.

<u>Budget limit for dynamic and static global monitoring, and the monitoring of some local vulnerabilities: € 50,000 per span (with an average length of 35 m).</u>

RESTRAINS & DIFFICULTIES

- **Restrains, difficulties and solutions connected to internet of things (IoT)**:

The IoT-based health monitoring system in general consists of sensors, a central server, and a user interface.
The architecture of the IoT system defining the conceptual framework of the BIM4CE bridge monitoring system entails the **sensing layer, the communication layer and the application layer.** Real time data collection is the corner stone of IoT based health monitoring system.

The sensing layer is the section of the IoT framework that is responsible for the acquisition of measurements by sensors.
The main elements of the sensing layer are the **sensor nodes.** Each sensor node consists of transceiver, power supply, processor, memory and sensors. The sensors are placed at various locations on bridges to collect data on temperature, humidity, vibration, and other parameters. In a sensor node, the energy requested to the power supply system mainly depends on the consumption of the active sensors and the transceiver. Over the last few years, there has been a tendency to increase the intelligence on board the sensor node (intelligence on-the-edge); this is a further factor to take into consideration when sizing the power supply system.

Usage of network cameras:
It is important to consider the use of network cameras for traffic monitoring. This is due to the fact that the estimation of vehicle loads is a rising research hotspot in bridge structure health monitoring and computer vision-based approaches, coupled with Weigh-in-Motion (WIM) sensors measurements, are all promising ways for vehicle tracking on bridges. However, it is important to to be aware of restrictions posed by visual frames. When the visual fields of multiple cameras are not continuous, the shapes of the same vehicle in video frames of different cameras will be quite different, thus it is very important to apply **the re-identification technique of vehicles** and avoid having an overlapped visual filed.
Cameras for traffic monitoring (IP cameras) are not able to measure the actual weight of the vehicles. Therefore, an important application in the bridge monitoring system is to analyze the correlation between cameras monitoring and WIM sensors, enabling the possibility of measuring the dynamic weight of passing by units.

RESTRAINS & DIFFICULTIES

Finally, it is important to remember that the use of network cameras usually requires the availability of an electrical power supply system at their installation points.

The communication layer is the part of the framework that deals with protocols and technologies used to transmit the measurements acquired by sensors to a central server. For that, a wired connection or a wireless connection can be used. The choice of the communication depends on the following aspects:

- The availability of a wired connection along the bridge;
- The availability of power supply along the bridge;
- The simplicity of connecting new sensors with wired systems;
- The needs in terms of bandwidth and data rate for the sensor nodes.
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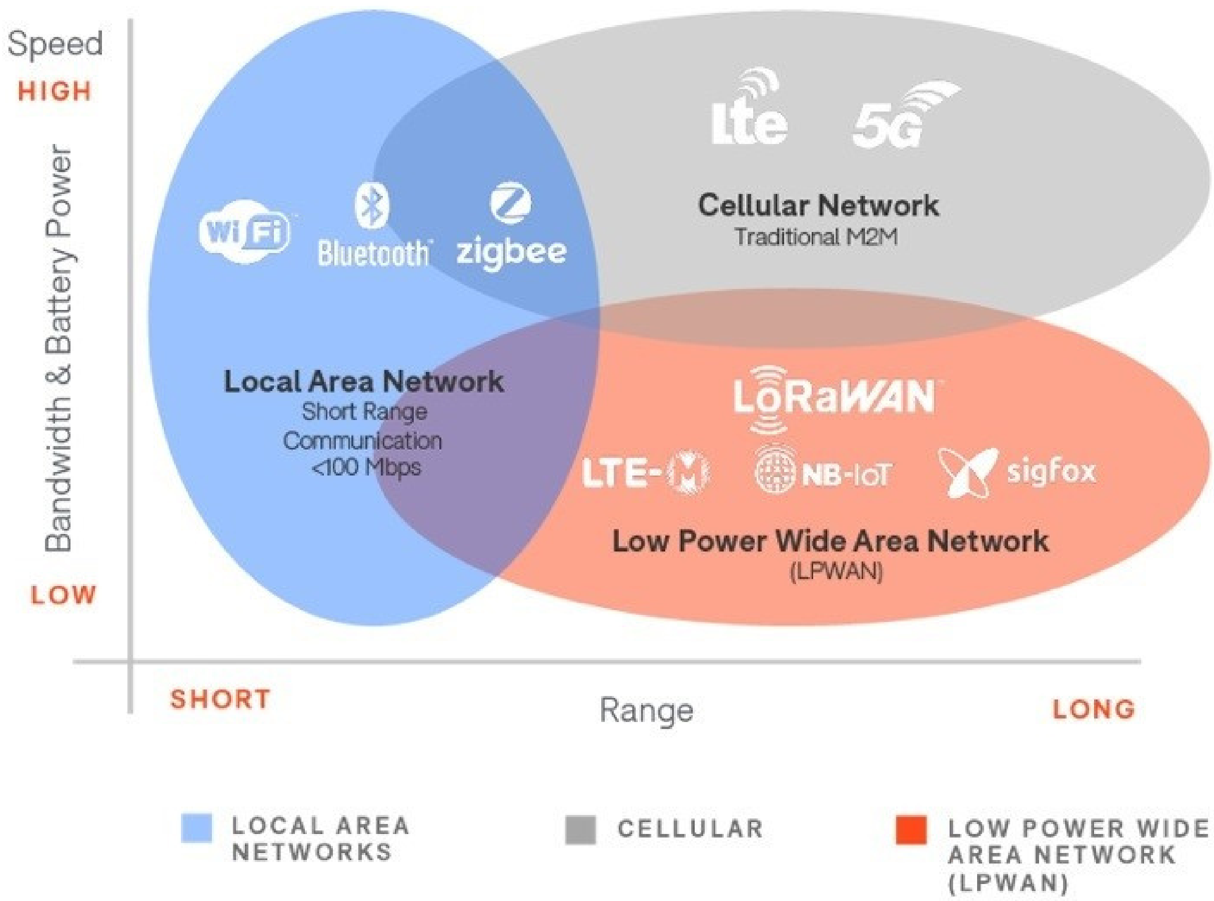
The most diffused wired infrastructures are the **optical fiber networks** (more simply optical networks) and EtherCAT communication protocols. Optical networks have three important elements: capacity, range and speed. The optical network is one of the fastest communication networks. Unlike copper based networks, the light pulses of an optical network may be transported quite a distance until the pulses are regenerated through an optical repeater device. Moreover, an optical network is less affected to external inference and attenuation and can achieve substantially higher bandwidth speeds than copper networks. **EtherCAT** is a high-performance Ethernet-based industrial communication protocol with support for various network typologies. It appeared in 2003, and since 2007 it has become an international standard. While in a conventional Ethernet network the master device uses separate commands to poll the slave devices, the EtherCAT protocol allows you to send only one command to poll and control several slave devices at once. This mechanism allows you to manage up to 65,535 devices in one network at high speed without restrictions in the network topology: line, bus, tree, star, or a combination of them. Moreover, to organize various topologies, hubs or switches are not needed, because the slaves themselves have multiple ports. A functionality that makes EtherCAT very attractive for SHM applications is the fact that it use a Distributed Clocks (DC) technology, meaning the time synchronization mechanism is implemented entirely in hardware.

RESTRAINS & DIFFICULTIES

In cases when there are no wired networks available along the bridge, it is necessary to use **wireless networks.** Selecting the appropriate wireless technology is one of the most fundamental decisions to make when building out an IoT system. wireless networks have relative strengths and weaknesses in terms of range bandwidth and battery power/life as shown by the diagram.



Moreover, LAN wireless technologies, like WiFi, Bluetooth and Zigbee, due to their short range coverage, can be used in contexts of bridges with small dimensions (< 100 meters) and in Line-of-Sight (LOS) conditions between transmitter and receiver/Access Point.

The technological revolution linked to **5G** gives rise to new collaborative models that are able to fuel the value chain of mobile telecommunication sector, thus accelerating development processes in vertical areas such as telemedicine, Smart City, Industry 4.0, infrastructure monitoring and transportation.

RESTRAINS & DIFFICULTIES

In the bridge monitoring framework, 5G technology can be very useful for CCTV cameras streaming and all the traffic monitoring applications connected to it.

LPWAN technologies are telecommunication techniques used for low consumption and extended coverage in IoT applications. LPWAN offers four fundamental characteristics for the world of IoT, which lead to the presumption of the persistence of this technology even in coexistence with 5G, especially in rural areas:

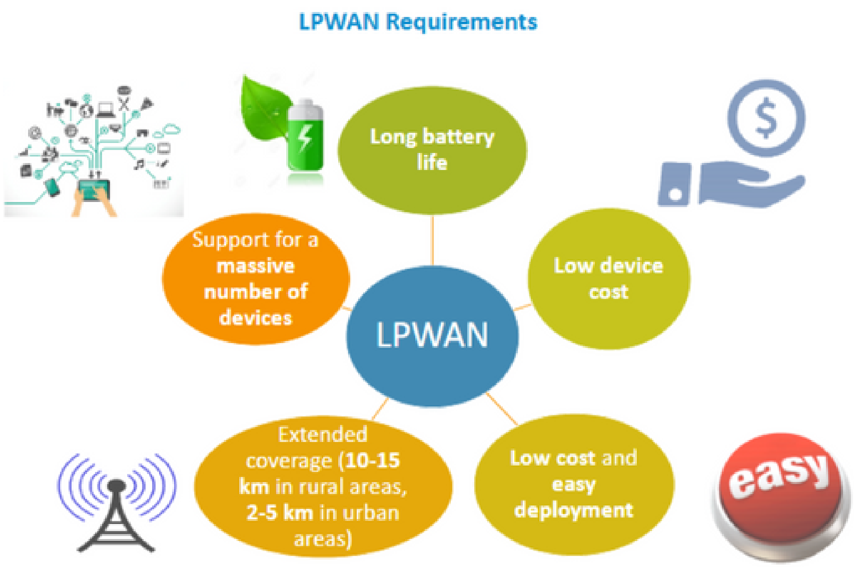
- low costs,
- broad coverage,
- low energy consumption,
- high density of devices manageable from a single cell.

Other interesting characteristics of IoT/LPWA networks are:

- low bitrates,
- nodes with low processing and storage requirements,
- small-sized nodes,
- low latency requirements,
- linear complexity network architecture.

Analyzing the characteristics in detail, it is clear that **LoRa/LoraWAN is the most suitable LPWAN technology for use in a digital bridge monitoring system due to its good payload length and latency performance.** LoRa is optimal due to its simplicity and installation costs, coverage, and low power consumption.

Summation of key features:



RESTRAINS & DIFFICULTIES

The application layer is responsible of data storage (e.g. data lake, database), as well as data elaboration (e.g. data analytics, machine learning, AI) and data visualization (e.g. dashboards). In modern times, it is crucial to effectively analyze raw data and transform it into information that is insightful and clear.
Data Lake is a storage repository that can store large amount of structured, semi-structured, and unstructured data. It offers high data quantity to increase analytic performance and native integration. Data elaboration for a dynamic BHM (Bridge Health Monitoring) system have made huge developmental steps thanks to computational intelligence and the use of data-driven approaches based on methods of Artificial Intelligence (AI) and Machine Learning.

IoT offers significant advantages like increased efficiency and data-driven decision-making. IoT devices capture and transmit data in real-time. However, most IoT devices lack data protocols and security requirements. **Security and privacy** concerns represent most notable drawbacks of IoT.
Striking a balance between innovation and security represents a crucial focal point. IoT security is affected by the **cost**, **changes throughout its evolution** and scope of the **safety measures** taken. All three mentioned factor represent major considerations.

References:

- *D.1.2.1: REPORT OF STATE OF THE ART OF BRIDGE MONITORING IN CENTRAL EUROPE*
- *D.1.2.3 WHITE PAPER DOCUMENTING NEEDS & REQUIREMENTS RELATED TO DIGITAL BRIDGE MONITORING SYSTEM*
- *D.1.3.1.: REPORT ON EXISTING BRIDGE TYPES IN CE INCLUDING CRITERIA FOR SELECTION FOR TARGET BRIDGE TYPE*
- *1.4.2: CONCEPTUAL FRAMEWORK FOR APPLICATION OF DIGITAL MONITORING SYSTEM*