GUIDELINES FOR DATA ACQUISITION, PROCESSING, AND QUALITY ASSURANCE

IM-SAFE.EU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Document Information

Name	Remark
Document Name	Guidelines for data acquisition, processing, and quality assurance
Version No.	V1.0
Due date Annex I	15/07/2020
Report date	30/04/2022 (last updated in 27/04/2022)
Number of pages	167
Lead Author	Ana Sánchez Rodríguez (Uvigo)
Other Authors	María Varela (INSITU), Sara Garrido (INSITU), David Lago (INSITU), Miguel Rodríguez (INSITU), Rizal Sebastian (TNO), Michel Böhms (TNO), Ioana Giurgiu (IBM)
Dissemination level	Public

Document history

Ver.	Date	Remark	Author	Checked by
Rev. 0.1	09/07/2021	Creation of the document	A. Sánchez	M. Varela, R. Sebastian, I. Giurgiu
Rev. 0.2	04/10/2021	First draft for revision	All	D. Allaix
Rev. 0.3	20/10/2021	Amendments on structure and content	All	A. Sánchez
Rev. 0.4	15/04/2022	Document for reviewers	All	M. Böhms, I. Alovisi, M. Weise
Rev. 0.5	22/02/2022	Amendments from reviewers	All	A. Sánchez
Rev. 0.6	27/04/2022	Document for approval	All	F. Cinquini and A. Bigaj-van Vliet
Rev. 1.0	30/04/2022	Document Uploaded	All	A. Bigaj-van Vliet

Document approval

Ver.	Date	Approval	Project's Role	Beneficiary
Rev. 1.0	30/04/2022	A. Bigaj-van Vliet	Coordinator	TNO

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Preface

This deliverable is part of the H2020 CSA IM-SAFE project and is the outcome of the first task of work package 4 (Digitalisation as enabling technology, task 4.1: Data acquisition and quality assurance). It will help to set the basis of the proposal for the mandate to the European Committee for Standardization (CEN).

Task leader: Universidade de Vigo (UVIGO)

Contributors: INGENIERÍA INSITU S.L. (INISTU)

IBM Research GmbH (IBM)

NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK (TNO)

In WP4, the relation with future standards in monitoring with the open IT standards is given, together with the data platforms available to manage different monitoring iformation and the data analytic technologies needed for processing those data.

This document provides a review of a particular seleciton of surveying technologies, including their main aspects with reference to the information that they collect. Then an insight on how those data should be managed and the security behind the platforms used is given.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Executive summary

This document aims to offer a detailed description of the main aspects that should be considered when working with monitoring data. This document is divided into four main chapters:

- Data collection, providing a general overview of a catalogue of surveying technologies (linked with IM-SAFE project deliverable D2.1 (Longo, et al., 2022) and IM-SAFE Semantic wiki https://imsafe.wikixl.nl/index.php/)
- Data pre-processing, ensuring the quality of data to be provided to the end user and with a focus on the technologies in IM-SAFE project deliverable D2.1 (Longo, et al., 2022)
- Data storage and management, studying the EU developments regarding data platforms and data integration
- Data security, ensuring confidentiality, integrity, and availability of data.

Table of Content

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

1. Problem statement

1.1 Introduction

The architecture, engineering, and construction (AEC) sector accounts for up to 9% of EU gross domestic product and more than 6% of European employment, making it a key sector in the industry. The digital transformation of this sector is associated with an enormous production of data. But the issue is no longer how to collect as much measurement data as possible, but how to integrate this within a platform in a standardised way. In addition, there are potential issues in relation with data collection that need an appropriate policy framework. These legislative barriers, together with the technological and social ones need to be addressed to achieve future safety and security goals.

The appearance of new technologies is leading the way for more sustainable and interconnected infrastructures. This will be given by the use of sensor data and IoT (internet of things) in the sector together with georeferenced data (i.e. GIS, geographical information system). Therefore, data analytics is crucial to know the current state of the infrastructure, and will help towards the efficient management of assets.

At present and in the future, the main issue is how to collect and exploit meaningful data throughout the lifecycle of infrastructure assets to further allow both human experts and machines (computers) to make accurate diagnostics, predictions, and decisions. Therefore, the objectives of IM-SAFE project in relation with this issue are:

- Generating an overview of the procedures and the output of data acquisition using various measurement devices, sensing technologies, 3D laser scanning techniques, and other relevant devices to collect measurement data; and specifying interfaces for monitoring and scanning data, such as point cloud data and sensor's value time.
- 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, structural 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).
- Sensor data processing and diagnostics:
  - Proposing guidelines for data processing at sensor level, with a stress on the reliability of the measurements.
  - Special attention should be given to standards for monitoring devices, such as IoT standards, standards for fibre optic sensors, level of details for 3D scan, size and format of data output from devices to be re-useable, etc.
  - Developing criteria for the successive surveying campaigns for updating the sensors. The campaigns include: (i) Georeferenced frame, i.e., the global location on the bridge; (ii) Alignment of sensor data, relative alignment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

1.2 Objectives of the deliverable

The present document is written in the context of the IM-SAFE project for the digitalization of information in the field of structural health monitoring. Considering this, the specific aspects addressed by this deliverable are:

- **Data collection**: Standardisation for the design of monitoring systems, from the point of view of the location of the data, the analysis on the data itself throughout the complete transmission pipeline; API to automatically send the post-processed data to a cloud server, which is accessible from a browser and allows for further post-processing; fundamental requirements on security, flexibility, bandwidth, and licensing restrictions.
- **Data processing and storage technology**: Considering the shift from databases and warehouses at fixed/predefined locations towards distributed and more fluid data processing, such as the so-called data lakes and data spaces; as well as the open standardisation approach to data sharing, such as the International Data Space (IDS) association, which aims to create a reference architecture to foster the development of data eco-systems and market places.
- **Data quality assurance**: Addressing the Data Quality Assurance Framework and Blockchain models.

1.3 Content

The first chapter of the document includes the present problem statement, which is addressesd by the introduction to the document, the objectives of this deliverable and this present section. Chapter 2 provides an overview on the requirements given by the data gathered through the sensors by means of storage, transmission, and data structure needs. It also includes information about interfaces for monitoring and scanning data, as well as a cost benefit analysis of the surveying technologies considered within this project. In Chapter 3 sumarises the procedures used in the acquisition or pre-processing process of different surveying technologies to make quantitative or qualitative assessments of the error committed. The necessary parameters for performing a quality control of the data are presented. Then, a proposal for the integration of as-built sensor data with digital as-planed and maintenance data is performed in Chapter 4. And finally, Chapter 5 deepens into data security and the existing strategies to ensure it.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2. Data[1] collection[2]

2.1 Purpose

The acquisition technology depends heavily on the purpose of the data acquired. IM-SAFE takes care of the structural/civil engineering part of transport infrastructures. This encompasses issues such as the causes affecting the structural performance of infrastructure, monitoring and maintenance or transport demands and regulations. In general, the purpose of an exploration through a certain survey technology is the generation of a specific product that can help to measure the state of the infrastructure, now or in the future.
The following are the most common purposes:

- Preservation: actions focused on infrastructure conservation.
- Monitoring: continuous observation of the infrastructure behaviour in order to know its condition during service life.
- Asset management and inventory, which are necessary to dispose of a set of relevant elements of the infrastructure and their properties so that they can be analysed in order to store and monitor their status.
- Maintenance: actions aimed at preserving the good condition of infrastructures to avoid deterioration.
- Safety: to make the use of the infrastructure as safe as possible through all the activities mentioned above.

2.2 Infrastructure and scenarios

This project contemplates two basic types of general infrastructures: bridges and tunnels located in roads and railways.

The different characteristics of the infrastructure and the study's purpose give rise to different scenarios, which will determine which are the most appropriate techniques to adopt. In this sense, the ways of working (and therefore the costs) changes substantially from one scenario to another.

Aspects related to the application of the survey technology to the all infrastructure, or to specific elements, the construction materials or the type of environment in which the structure is located, among others, will be taken into account.

2.3 Interfaces for monitoring and scanning data

This section specifies the required characteristics of the interfaces, which are defined below, and that will operate between the sensors and the interfaces for monitoring and scanning. It also provides recommendations on existing interfaces based, where possible, on free solutions.

[1] Data: Discrete and objective observations, facts and/or records of events with a potential to be transformation into applicable information.

[2] Data collection: Gathering and sampling data, including planning, preparing and conducting the field work previous and independent of further processing (needed to) to obtain the data ready for analysis.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.3.1 Definition of interface

An interface is an interconnection element between two independent physical or logical components that are part of the same system. The set of objects used in a software tool to communicate to the user with the system is also called interface.

The physical, logical and user interfaces allow communication at different levels and visualisation, enabling the exchange of information.

Interfaces design is a very important part of systems engineering, it involves the design of a complete system architecture detailing its components and connections.

The implementation of the designed interfaces will be different depending on the nature of the components to be connected, they may be wiring, wireless, firmware, web services, executables, etc. So, each case will need a specific solution that will have to be approached in a different way.

2.3.2 IM-SAFE interfaces requirements

The scope of this project involves the collection of data in a specific space delimited by the infrastructure environment and its monitoring, which adds the time variable and results of multiple data coming from an infrastructure, taken at different points in different time intervals.

Furthermore, the systems analysed within the scope of the IM-SAFE project can be understood as a system composed of two large components, which in turn are made up of smaller sub-components. These two large components or subsystems are, on the one hand, the capture systems and the different elements that form part of them (sensors, cables, platforms, etc.) and, on the other hand, the data storage devices, whether physical or virtual.

- **The capture systems**

The results of this project will define different procedures related to specific capture systems to work efficiently in a particular scenario.

Each one of these systems is composed of several sensors and other technological components which need to be connected both physically (if wired) and logically in order to work in an efficient way.

Interfaces between capture system components are needed to gather data from sensors and to tranfer them to the local unit/server/cloud and for synchronisation. It involves the physical and logical connections of the system and may include temporary data storage on local disks.

- **The data storage**

To be able to save the type of information that inspection and monitoring of infrastructures sector requires permanently, it is necessary to provide adequate file repositories or databases to successfully store this high-resolution information. The most efficient solution, which would allow the capacity of scaling, remote access, easy maintenance, and automatic backups is a cloud-based solution.

Another factor to be considered is whether the data requires automatic sending, or whether it will be sent manually by an operator. For each case, the interface will have a different configuration.

In the first case and also when monitoring is required, more complex interfaces will be needed to feed the data model in the set period. In this scenario, the interfaces will be implemented in the form of web services that will operate automatically and unattended, but not necessarily in real time.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

In the second case, the interfaces can be configured using common network protocols, such as those mentioned below:

- Hypertext Transfer Protocol (HTTP)
- File Transfer Protocol (FTP)
- File Transfer Protocol with Secure Sockets Layer (FTPS or FTP-SSL)
- Network File System (NFS)

In each survey technology specific section, the interfaces required for each technology, either between subcomponents of the system or between the system and the cloud file repository, will be mentioned.

2.4 Cost/benefit principles

In order to provide an overview of the cost-benefit ratio of different data acquisition technologies, some guidelines have been defined. In this way, it will be possible to draw up a balance sheet demonstrating the estimated effort related to the chosen solution and the costs involved in its implementation.

The costs to be taken into account for the implementation of each survey technology are those related to the material resources used and the personnel involved in the different phases of the process: preparation, acquisition, data processing, etc.

To this end, the partners in charge of each technology have been asked, based on their experience, to indicate the hourly cost of each employee profile and the costs related to the purchase or rental of the different components of the systems and equipment.

In the case of human resources, an attempt has been made to standardise costs and establish values as close as possible to the European average through the personnel cost tables in public tenders. It should be borne in mind that these costs tend to increase over the years, but the important thing is to determine the protocols and guidelines for determining them.

The costs of material resources have been provided by the partners in charge of each survey technology. When the purchase cost of materials or devices is taken into account rather than their rental cost, the amortisation cost of each component per day is calculated. For this it is necessary to take into account the residual value of the resource (the estimated value that the asset could have at the end of its service life) and the estimated number of uses of the resource over a year. In the case of both purchased and rented equipment, where a range of costs is given, the highest value has been used.

It should be mentioned that in no case travel costs to the place where the data collection takes place have been taken into account. In addition, in some cases the costs have been modified and expressed in different units than those provided to match the rest.

The yields associated with each task carried out in the different phases of application of the technique have also been established, i.e. the duration of each task and the different resources necessary for its execution, both human and material. They have been included in table format in the "Performance" section of each technology.

Taking all this information into account, a budget was drawn up for the application of each technique. Overheads of 13% and a profit of 6% (Real Decreto 1098/2001) have been applied to the cost of each resource, thus obtaining an approximate amount for the application of each survey technology.

For each case, the assumptions made are indicated in order to be able to generalise.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.4.1 Employee profiles

As mentioned above, in order to be able to estimate the costs involved in using each technique, it is also necessary to take into account the personnel costs depending on the profiles and the time required for the work. For this purpose, the different profiles of professionals needed to carry out the different phases of the procedure have been defined. For each technique, one or more will be required, depending on the case:

- Coordinator who is responsible for the planning of the work to be performed and for the selection of operators and their coordination and supervision.
- Operators who are responsible for the configuration and the handling of equipment and scanning operations, as well as for driving the terrestrial laser scanning vehicle where applicable.
- Security personnel for supervision in the case of static scanning on road or railway, as well as in the preparation of vehicles for mobile scanning on site.
- Railway driver in cases where mobile scanning is performed by railway tracks with the sensors installed on a railway wagon.
- Engineer who is responsible for planning tasks, processing data and structural interpretation.
- Developers for implementation of algorithms which allow data management and processing.
- Technician for data processing.

2.5 Survey Technologies

In the following subsections, for each of the survey technologies considered, some key aspects such as parameters to be determined, different application scenarios, methodology, phases and tasks, system or equipment components, etc. are discussed. For more details please refer to the annexes of IM-SAFE project deliverable D2.1 (Longo, et al., 2022).

Based on this information it is intended to define, among other things, the protocols for data collection and storage and the evaluation of the cost-benefit ratio.

2.5.1 Acoustic emission (AE)

2.5.1.1 Purpose and main features

Acoustic emission testing is one of the most common and useful methods of non-destructive testing. These techniques are an inspection method that uses the release of ultrasonic stress waves to identify defects in construction materials. Thus, they are very useful for monitoring and maintenance work on infrastructures, bridges and tunnels, especially those zones which are not visible using a typical monitoring system, like foundations.

In this method it is possible to use several sensors and their amount will depend on the complexity of the structure, its size and on the type of material tested. Different types of sensors can be applied: piezoelectric transducers, piezoelectric sensors, strain gauges.

AE methods can be combined with shaking tables tests for determine the progressive damage state of tunnel lining. Data is collected in real time and this allows short-term monitoring to identify and describe the lining damage caused by the seismic performance of the tunnel. Tunnel damage analysis is carried out by representative acoustic parameters as amplitude, counts, energy etc. for a specific period of time. This is novel approach thought – acoustic emission sensor are combined with strain sensors systems as well.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Acoustic emission testing is applicable for the whole structure. However, it can be used as well for specific elements such as: knots and stringers, hanger connections, link pin connections and copes.

Thanks to the use of these sensors, it is possible to characterise certain parameters that allow monitoring the state of the infrastructure and determine which elements need maintenance. All of them refer to the whole structure, except delamination which refers to asphalt on concrete. These are as follows:

- Cracks: crack opening (cm)
- Delamination: depth of delamination [cm] from the outermost layer of the slab to the bottom of the slab OR from the outermost layer of the slab to the outermost layer of the reinforcement [cm]
- Rupture: distance from the beginning of the stirrup (cm)
- Displacement: vertical, horizontal displacements (mm)
- Reinforcement failure
- Loss of section
- Debonding
- Deformation
- Holes
- Wire breaks

2.5.1.2 Scenarios definition

The diagnostic acoustic emission method has been used for the inspection of more than 100 kilometres of bridges and tunnels in Europe. When applying this technology to both infrastructures, the difference will be in the mounting location of the sensors.

Although some sensor settings may vary, the system set up will be the same, and therefore the application will not depend on the element of the structure to be studied, its material or the type of environment in which it is located.

The number of sensors used will depend on the different working conditions such as temperature and humidity of the environment and will determine the specific type of sensor and the type of mounting.

2.5.1.3 Technology characteristics

The acoustic emission sensors are designed for both global and local measurements. For global purposes, help with assessing the structural integrity, while in local uses detecting specific areas of damage. Analysis is carried out by representative acoustic parameters as amplitude, counts, energy etc. for a specific period of time, so the measures will be recorded automatically in a digital and static way.

It is possible to make several measures at the same time or several measures in a specific period of time which allow real time monitoring 24/7 and so that inspections for short periods and long term can be performed.

This technology gives rise to graphic data like 3-D graphs and other type of information that can be stored in databases and visualized on screens.

In addition to the acoustic emission sensors, the equipment must be equipped with signal cables, a preamplifier, a main amplifier, signal DC/ power cable, AE acquisition and analysis system, a host computer, AE software and a couplant.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.1.4 Methodology: phases and tasks

When installing the sensors, it should be done using high-vacuum grease with adhesive tape to enhance the coupling performance at the interface between the material and the sensor. In addition, it should be noted that measurements may be affected by the presence of other unwanted signals which may mask those from cracks, cable breaks or other defects.

In order to obtain the required data, different phases need to be carried out. Some of these, in turn, can be divided into a number of tasks:

1. Planning. It involves:
   - Decision regarding the places of mounting,
   - Decision regarding the way of mounting: through clearance hole, through drill and tap, with the mounting disc or with extension tab.
2. Preparation. It involves:
   - Cleaning the surface
   - Mounting the sensors on the structure.
3. Calibration. It involves:
   - Probing with an oscilloscope to set gain and threshold levels
   - Reading the values of the parameters of the EA signals, generated by the standard source
4. Detection/Data collection/Supervision
5. Data processing and analysis
6. Validation

2.5.1.5 Interfaces and Connections

The components of the acoustic emission systems communicate with each other via different signal cables or DC signal/power cables. The connection to the host computer shall be made via serial ports. The data can be stored on memory cards built into the equipment for later analysis on a computer. For this purpose, memory card readers shall be used to access the information from the PC. It is also possible to transfer the data automatically to the base station using wireless interfaces. The data will be stored in files that can be displayed on the screen. It will also be possible to store them in databases for further processing. Therefore, a user interface is needed that implements services for data management and visualisation.

2.5.1.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.1.6.1 Personnel

Human resource	Cost (€)	Unit
Bridge inspector	26	Hour
Operator	15	Hour

Table 2.1 – Human resources for AE technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.1.6.2 Material resources

Material resource	Cost (€)	Unit
Acoustic sensor	1271,96	Device
Preamplifier	170,57	Device
Main amplifier	823,62	Device
Computer-based data acquisition device (+manufacturer software)	9000	Device
Coupling grease for sensor mounting	46,80	Bottle
Connecting cables	11,96	2m
Portable version of 4-channel acoustic emission test equipment	6017,29	set

Table 2.2 – Material resources for AE technique

Since a purchase cost per device is given, the amortisation value is calculated:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Acoustic sensor	1.271,96€	10,00%	2	70,00	8,18€
Preamplifier	170,57€	10,00%	2	70,00	1,10€
Main amplifier	823,62€	10,00%	2	70,00	5,29€
Computer-based data acquisition device (+manufacturer software)	9.000€	10,00%	5	100,00	16,20€
Coupling grease for sensor mounting	46,80€	10,00%	1	50,00	0,84€
Connecting cables	11,96€	10,00%	2	70,00	0,08€
Portable version of 4-channel acoustic emission test equipment	6.017,29€	10,00%	2	70,00	38,68€

Table 2.3 – Amortisation of materials used in AE technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.1.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	Decision on mounting places of the sensors	1	Hour
Planning	Trial period to determine the best location	2	Hour
Preparation	Cleaning the contact surfaces	0,20	Per sensor
Preparation	Coating the surfaces with grease	0,20	Per sensor
Data acquisition	Calibration	1	Hour

Table 2.4 – Duration of tasks in AE technique

Task	Resource	Hours
Planning	Bridge inspector	1-3
Preparation	Operator, PC, software	1-3
Data acquisition	Operator, PC, software	1-3

Table 2.5 – Resources used in AE technique tasks

2.5.1.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/ Unit	Cost	%O	O	% B	B	Budget
Bridge inspector	hour	3,00	26,00€	78,00€	13,00%	10,14 €	6,00%	4,68 €	92,82 €
Operator	hour	6,00	15,00€	90,00€	13,00%	11,70 €	6,00%	5,40 €	107,10 €
Computer-based data acquisition device (+manufacturer software)	day	1,00	16,20€	16,20€	13,00%	2,11 €	6,00%	0,97 €	19,28 €
Acoustic sensor	day	1,00	8,18 €	8,18€	13,00%	1,06 €	6,00%	0,49 €	9,73 €
Portable version of 4-channel acoustic emission test equipment	day	1,00	38,68 €	38,68€	13,00%	5,03 €	6,00%	2,32 €	46,03 €
				231,06€		30,04 €		13,86 €	**274,96 €**

Table 2.6 – Breakdown of costs and benefits for the budgeting of the AE technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.2 Aerial UAV. Optical Payloads

2.5.2.1 Purpose and main features

Unmanned Aerial Vehicles (UAV) or, following the normative, Remotely Piloted Aerial Systems (RPAS) are a kind of aerial platforms that can carry on board light-weight sensors and perform surveying tasks in infrastructures as a basis for maintenance. Obtaining periodic data over time supports the comparison of the different epochs of the maintenance and thus enabling the monitoring of the infrastructures.

This technique is applied mainly in the bridge inspection and monitoring, and is highly dependent on the sensors onboard and the trajectory to be followed by the platform.The most frequent sensors include:

- Optical cameras for visual inspection through image processing
- Multispectral and thermographic cameras
- LiDAR for collecting points clouds
- RADAR payloads

Due to the higher resolution of optical cameras, image processing techniques may be preferred over other sensors such as LiDAR or RADAR, to detect the boundaries of the defects.

So, the parameters and the structure information obtained, depend on the sensors mounted. But in general, it is possible to detect damage to the structure such as:

- Cracks, their thickness and extent
- Gaps between the end of kerf plate and sawn kerf in the brace

The most challenging objects and components to be inspected are those where satellite navigation systems are not robust due to occlusions or spurious reflections, the so-called GNSS-denied positions. For GNSS-denied positions, the inspection with RPAS needs for a solution of the navigation based on sensors different from GPS.

2.5.2.2 Scenarios definition

The main differences in RPAS inspection and tracking are determined by the type of sensor integrated in the navigation platform. Thus, when it comes to collecting data in tunnels, there are specific solutions based on dead reckoning navigation and (simultaneous location and mapping) slam-like techniques.

Similarly, it is possible to analyse different elements of an infrastructure, like girders, but is necessary to have into account the navigation problems described above, which will affect the monitoring of objects and components, must be taken into account.

In addition, on-board sensors can be affected by materials, so it is essential to refer to the specific characteristics and specifications of each type of sensor.

However, there are no major differences or salient factors to be taken into account depending on the environment (road, rail) in which the structure to be studied is located.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.2.3 Technology characteristics

The variety of sensors that can be used in this technique allows digital measurements to be taken both automatically and manually, and on the move.

It is possible to take a single measurement or several measurements over a specific period of time, thus facilitating spot inspections and monitoring of the structure over time.

The information thus collected will be alphanumeric, numeric and graphical and will be stored in plane text, binary files, DB and common image formats.

For data capture and subsequent data processing, the following elements and tools that make up the equipment and facilitate pre-processing must be available:

- UAV platform
- Payload (i.e. the on-board sensors)
- Topographic trajectory definition software
- Ground control system (GCS)
- Communication systems
- Devices for data storage

2.5.2.4 Methodology: phases and tasks

One of the main factors to take into account when working with UAVs is the environmental conditions, which can affect the trajectory of the vehicle. Therefore, special attention should be paid to:

- Wind speed, so that the UAV can maintain flight capability.
- Visibility, which affects both optical loads and flight performance.
- Protection grade with respect to rain and water

Considering these aspects, the use of this data acquisition technique involves the following phases and tasks:

1. Planning. It includes next tasks:
    - Determining the target: areas and data to be captured.
    - Preliminary site check
    - Flight planning: take-off and landing locations, flight speeds and heights, image scale limitations and preliminary safety study.
2. Aircraft navigation systems calibration
3. Data capture
4. Processing
5. Quality control: Data analysis and assessment of overall accuracy.

2.5.2.5 Interfaces and Connections

The connection between the different elements that make up the system is made through the different communication ports. The motherboards of each type of sensor are connected to each other mainly by means of serial or I2C ports, in the latter case, using the protocol of the same name. The port includes two communication cables, SDA and SCL, and allows multiple devices to be connected to the same bus. In addition, this protocol allows having a

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

confirmation of the received data. However, it is also possible to use other protocols, such as Serial TLL or CAN Bus.

Sensors usually are compatible with different open networks for advanced traceability, and maintenance. Different networks are available: EtherNet/IPtm , DeviceNet, PROFIBUS, EtherCAT or CC-Link.

The collected data can be stored on remote servers that includes the software for data analysis, results presentation and automatic alerting, so FTPS or TCP/IP protocols will be used to transfer the data. Advanced visualisation and analysis can be performed with real-time data transferred over IO-link.

2.5.2.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.2.6.1 Personnel

Human resource	Cost (€)	Unit
Engineer	60	Hour
Operator	50	Hour

Table 2.7 – Human resources for Aerial UAV technique

2.5.2.6.2 Material resources

Material resource	Cost (€)	Unit
DJI Matrice 300 RTK UAV with RGB photogrammetry sensor	1500	Day
DJI Matrice 300 RTK UAV with H20 Inspection Sensor	1700	Day
DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor	1900	Day
DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry	1200	Day
DJI Mavic 2 Enterprise Dual UAV with RGB sensor	975	Day
Aeronautical management of permits to fly	190	Flight

Table 2.8 – Material resources for Aerial UAV technique

As a reference, it is enough to fly a bridge 30 metres wide and 350 metres long in one hectare.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.2.6.3 Performance

This section shows an estimate of the time needed to carry out the different tasks with each equipment, as well as the resources (material and human) used in each one.

- DJI Matrice 300 RTK UAV with RGB photogrammetry sensor

Phase	Task	Duration (hours)	Unit
Planning	Planning	0,4	Flight
Calibration	Calibration	0,3	Flight
Capturing	Capturing	0,1	Ha
Processing	Image processing	3,5	Flight
Quality Control	Quality control	2,5	Flight

Table 2.9 – Duration of tasks with DJI Matrice 300 RTK UAV with RGB photogrammetry sensor

Task	Resource	Hours
Planning	DJI Matrice 300 RTK UAV with RGB photogrammetry sensor, Engineer	0,4
Calibration	DJI Matrice 300 RTK UAV with RGB photogrammetry sensor, Operator, Engineer	0,3
Capturing	DJI Matrice 300 RTK UAV with RGB photogrammetry sensor, Operator, Permits	0,1
Image processing	Engineer	3,5
Quality control	Engineer	2,5

Table 2.10 – Resources used in flight with DJI Matrice 300 RTK UAV with RGB photogrammetry sensor

- DJI Matrice 300 RTK UAV with H20 Inspection Sensor

Phase	Task	Duration (hours)	Unit
Planning	Planning	0,6	Flight
Calibration	Calibration	0,3	Flight
Capturing	Capturing	2,2	Ha
Processing	Image processing	4,5	Flight
Quality Control	Quality control	2,5	Flight

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table 2.11 – Duration of tasks with DJI Matrice 300 RTK UAV with H20 Inspection Sensor

Task	Resource	Hours
Planning	DJI Matrice 300 RTK UAV with H20 Inspection Sensor, Engineer	0,6
Calibration	DJI Matrice 300 RTK UAV with H20 Inspection Sensor, Operator, Engineer	0,3
Capturing	DJI Matrice 300 RTK UAV with H20 Inspection Sensor, Operator, Permits	2,2
Image processing	Engineer	4,5
Quality control	Engineer	2,5

Table 2.12 – Resources used in flight with DJI Matrice 300 RTK UAV with H20 Inspection Sensor

- DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor

Phase	Task	Duration (hours)	Unit
Planning	Planning	0,4	Flight
Calibration	Calibration	0,3	Flight
Capturing	Capturing	0,1	Ha
Processing	Image processing	5,5	Flight
Quality Control	Quality control	2,5	Flight

Table 2.13 – Duration of tasks with DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor

Task	Resource	Hours
Planning	DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor, Engineer	0,4
Calibration	DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor, Operator, Engineer	0,3
Capturing	DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor, Operator, Permits	0,1
Image processing	Engineer	5,5

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Quality control	Engineer	2,5

Table 2.14 – Resources used in flight with DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor

- DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry

Phase	Task	Duration (hours)	Unit
Planning	Planning	0,4	Flight
Calibration	Calibration	0,2	Flight
Capturing	Capturing	0,13	Ha
Processing	Image processing	5,5	Flight
Quality Control	Quality control	2,5	Flight

Table 2.15 – Duration of tasks with DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry

Task	Resource	Hours
Planning	DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry, Engineer	0,4
Calibration	DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry, Operator, Engineer	0,2
Capturing	DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry, Permits	0,13
Image processing	Engineer	5,5
Quality control	Engineer	2,5

Table 2.16 – Resources used in flight with DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry

- DJI Mavic 2 Enterprise Dual UAV with RGB sensor

Phase	Task	Duration (hours)	Unit
Planning	Planning	0,4	Flight

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Calibration	Calibration	0,2	Flight
Capturing	Capturing	0,16	Ha
Processing	Image processing	3,5	Flight
Quality Control	Quality control	2,5	Flight

Table 2.17 – Duration of tasks with DJI Mavic 2 Enterprice Dual UAV with RGB sensor

Task	Resource	Hours
Planning	DJI Mavic 2 Enterprice Dual UAV with RGB sensor, Engineer	0,4
Calibration	DJI Mavic 2 Enterprice Dual UAV with RGB sensor, Operator, Engineer	0,2
Capturing	DJI Mavic 2 Enterprice Dual UAV with RGB sensor, Operator, Permits	0,16
Image processing	Engineer	3,5
Quality control	Engineer	2,5

Table 2.18 – Resources used in flight with DJI Mavic 2 Enterprice Dual UAV with RGB sensor

2.5.2.6.4 Cost/benefit analysis

The following tables show an estimate of the budgets drawn up for the inspection of a bridge. The different equipment presented in the Table 8 has been taken into account.

Resource	Unit	Units	Cost/ Unit	Cost	%O	O	% B	B	Budget
DJI Matrice 300 RTK UAV with RGB photogrammetry sensor	day	1	1500	1.500,00€	13,00%	195,00 €	6,00%	90,00 €	1.785,00 €
Engineer	hour	6,7	60	402,00€	13,00%	52,26 €	6,00%	24,12 €	478,38 €
Operator	hour	0,4	50	20,00€	13,00%	2,60 €	6,00%	1,20 €	23,80 €
Aeronautical management of permits to fly	flight	1	190	190,00€	13,00%	24,70 €	6,00%	11,40 €	226,10 €
				2.112,00 €		274,56 €		126,72€	**2.513,28 €**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table 2.19 – Breakdown of costs and benefits for the budgeting with DJI Matrice 300 RTK UAV with RGB photogrammetry sensor

Resource	Unit	Units	Cost/ Unit	Cost	%O	O	% B	B	Budget
DJI Matrice 300 RTK UAV with H20 Inspection Sensor	day	1	1700	1.700,00 €	13,00%	221,00 €	6,00%	102,00 €	2.023,00 €
Engineer	hour	7,9	60	474,00€	13,00%	61,62 €	6,00%	28,44 €	564,06 €
Operator	hour	2,5	50	125,00€	13,00%	16,25 €	6,00%	7,50 €	148,75 €
Aeronautical management of permits to fly	flight	1	190	190,00€	13,00%	24,70 €	6,00%	11,40 €	226,10 €
				2.489,00 €		323,57 €		149,34 €	**2.961,91 €**

Table 2.20 – Breakdown of costs and benefits for the budgeting with DJI Matrice 300 RTK UAV with H20 Inspection Sensor

Resource	Unit	Units	Cost/U nit	Cost	%O	O	% B	B	Budget
DJI Matrice 300 RTK UAV with multispectral photogramme try sensor	day	1	1900	1.900,00 €	13,00%	247,00 €	6,00%	114,00 €	2.261,00 €
Engineer	hour	8,7	60	522,00€	13,00%	67,86 €	6,00%	31,32 €	621,18 €
Operator	hour	0,4	50	20,00€	13,00%	2,60 €	6,00%	1,20 €	23,80 €
Aeronautical management of permits to fly	flight	1	190	190,00€	13,00%	24,70 €	6,00%	11,40 €	226,10 €
				2.632,00 €		342,16 €		157,92€	3.132,08 €

Table 2.21 – Breakdown of costs and benefits for the budgeting with DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor

Resource	Unit	Units	Cost/U nit	Cost	%O	O	% B	B	Budget
DJI Matrice 300 RTK UAV with multispectral photogramme try sensor	day	1	1200	1.200,00 €	13,00%	156,00 €	6,00%	72,00 €	1.428,00 €
Engineer	hour	8,6	60	516,00€	13,00%	67,08 €	6,00%	30,96 €	614,04 €
Operator	hour	0,33	50	16,50€	13,00%	2,15 €	6,00%	0,99 €	19,64 €

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Aeronautical management of permits to fly	flight	1	190	190,00€	13,00%	24,70 €	6,00%	11,40 €	226,10 €
				1.922,50 €		249,93 €		115,35€	2.287,78 €

Table 2.22 – Breakdown of costs and benefits for the budgeting with DJI Phantom 4 multispectral RTK UAV with RGB sensor and multispectral sensor for photogrammetry

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
DJI Matrice 300 RTK UAV with multispectral photogrammetry sensor	day	1	975	975,00€	13,00%	126,75 €	6,00%	58,50 €	1.160,25 €
Engineer	hour	6,6	60	396,00€	13,00%	51,48 €	6,00%	23,76 €	471,24 €
Operator	hour	0,36	50	18,00€	13,00%	2,34 €	6,00%	1,08 €	21,42 €
Aeronautical management of permits to fly	flight	1	190	190,00€	13,00%	24,70 €	6,00%	11,40 €	226,10 €
				1.579,00 €		205,27 €		94,74€	1.879,01 €

Table 2.23 – Breakdown of costs and benefits for the budgeting with DJI Mavic 2 Enterprice Dual UAV with RGB sensor

2.5.3 Fibre Optic Sensors (FOS)

2.5.3.1 Purpose and main features

Fibre Optic Sensors are used in permanent monitoring of bridges and tunnels, to measure changes in static and dynamic parameters due to non-temperature effects such as different types of load (traffic, wind), thermal effect, evolution of the material properties or damages.

FOS technology allows measuring the bridge or tunnel performance under traffic loads and storing the information globally with expanding modern data storage solutions. Measurements can be performed automatically without the need of access to the tunnel or bridge and hence, monitoring can be made without disturbing the infrastructure construction or operation.

However FOS technology is used for monitoring of whole structures, it can be used also along the length of the structural element to which single fibre has been attached only. Thus, FOS is also suitable for single components as walls and columns.

Some of the advantages offered by fibre optics include:

- They do not require electricity and do not overheat, so they are very safe to use in hazardous or confined environments where there may be a risk of fire.
- They are immune to electromagnetic interference and do not generate it. Therefore, they can be used in high voltage environments without affecting measurements and without disturbing neighbouring electrical devices.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

In addition, FOS technique can be used for many sensors arrays depending on the objective of the measurements. This is a group of sensors placed vertically, linearly, non-linearly, etc. that adds new dimensions to the observation and therefore helps to estimate more parameters and improve the estimation performance. Those systems are working as a full monitoring circuit which can be modified in size depending on the needs. Some of them are: Distributed fibre optic sensing (DFOS), which delivers hundreds of strain and temperature sensing points inside the structure, Fabry Perot Interferometers (FISO), FOS/FBG or SOFO.

Applying this technique with the mentioned sensors, next parameters can be obtained:

- Characterisable parameters:
  - Strain (µm/m)
  - Temperature (Celsius degrees)
  - Acoustic noise (Hz)
  - Deformation (mm)
  - Displacement (mm)
- Presence of:
  - Cracks
  - Rupture
  - Holes
  - Wire break
  - Loss of section
  - Obstruction/impeding
  - Stirrup rupture
  - Deteriorated mortar joints
  - Shrinkage

2.5.3.2 Scenarios definition

The application and mode of operation of this technique is not affected by the type of structure or the elements in which it is to be applied. However, it will depend on the purpose of the measurements and the availability of places to mount the sensors, since where the sensors are to be mounted it is necessary to remove the paint coatings and clean the surface and after placement to apply epoxy paint for safety.

In terms of infrastructure material, this will affect the choice of sensors to be used. Factors such as spatial resolution, sampling frequency and the possibility to measure absolute/relative temperature have to be taken into account.

Finally, the type of environment in which the sensors are to be mounted must also be taken into account, as the conditions and difficulty will be different due to location and grade constraints.

For example, it is possible to use systems in underwater conditions. For this purpose, the fibre optic sensor is packaged in a stainless steel tube with one end open to allow contact with the surrounding water.

2.5.3.3 Technology characteristics

Fibre optic sensors allow automatic data collection in a digital form, which will be stored on one server. Performed measurements collect the data in motion under different loads.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

DFOS/FOS technology is used for a real-time monitoring 24/7. Multiple parameters (strain, temperature, displacement, bending, etc.) can be measured by, or derived from the same system, thus eliminating the need for multiple monitoring systems.

The information obtained with this technology can be graphic and numeric, and it will be stored in different file formats.

The necessary equipment to apply the technique is:

- Measurements optic fibres
- Reference optic fibres
- A coupler
- A battery powered reading unit
- An amplifier
- A portable PC
- An user navigation platform
- Software on-line for data processing

2.5.3.4 Methodology: phases and tasks

Optical fibres are very useful to measurements over long distances in harsh operating conditions. Their performance will depend on environmental conditions, so it will be necessary to assess which type of sensor to apply. Some factors to consider when choosing a sensor for monitoring are:

- Spatial resolution
- Sampling rate
- The ability to measure absolute/relative temperature

In the following, the different phases for data acquisition and the tasks they include are distinguished:

1. Planning. It involves:
    - Choice of the monitoring method (type of sensors)
    - Choice of the places of sensors mounting
    - Number of sensors to be used, executive sketch of the locations
2. Initialization - operational works, preparation of the surfaces on the bridge or tunnel in place of mounting etc.
3. Calibration. By pressing the set button on the amplifier. The sensing element (the optical fibre) is passive, FO sensors require no maintenance and no repeated calibration.
4. Trial period. It includes:
    - First reading after calibration of different parameters
    - Observation of the graphs in the software
5. Real-time monitoring
6. Processing of the data and analysis automatically in the software.
7. Validation of the data with statistical or heuristic methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.3.5 Interfaces and Connections

A fibre optic sensor system consists of a fibre optic cable connected to a remote sensor, an amplifier and other components via appropriate ports. The collected data is stored in files and automatically transmitted to a server, so it will be necessary to implement interfaces for secure data transmission using protocols such as FTPS.

This data can then be checked from a computer. This requires a graphical user interface and online software for pre-processing..

2.5.3.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.3.6.1 Personnel

Human resource	Cost (€)	Unit
Engineer	23,21	Hour
Operator	18,05	Hour

Table 2.24 – Human resources in FOS technique

2.5.3.6.2 Material resources

Material resource	Cost (€)	Unit
Full system for monitoring with 8 FOS sensors	1066,75	Set
Meritorical consultations	50	Hour
Portable PC	10094,98	Device
First readings with assistance of the manufacturer	1073,17	Set
Fibre optic sensor	127	Unit
Fibre optic sensor cable	117	300 mm
Detector	36,02	Unit
Fibre Optic receiver	23,73	unit

Table 2.25 – Material resources in FOS technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

The amortisation value of each device is then calculated on the basis of its purchase price:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Full system for monitoring with 8 FOS sensors	1066,75€	10,00%	2	100,00	4,80€
Meritorical consultations	50€	10,00%	2	100,00	0,23€
Portable PC	10094,98€	10,00%	2	100,00	45,43€
First readings with assistance of the manufacturer	1073,17€	10,00%	2	100,00	4,83€
Fibre optic sensor	127€	10,00%	2	100,00	0,57€
Fibre optic sensor cable	117€	10,00%	2	100,00	0,53€
Detector	36,02€	10,00%	2	100,00	0,16€
Fibre Optic receiver	23,73€	10,00%	2	100,00	0,11€

Table 2.26 – Amortisation of materials used in FOS technique

2.5.3.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	Choice of the monitoring system and way of mounting	1	hour
Initialization	Operational works	1-10 (depends on the complexity)	hour
Calibration	Setting the values	1-2	hour
Trial period	Real-time initial readings	1-24	hour
Real-time monitoring	-	24/7/1	Hour/days/year
Processing	-	0,2	hour
Validation	-	1-3	hour

Table 2.27 – Duration of tasks in FOS technique

Task	Resource	Hours
Planning	Engineer, operator	1-2
Initialization	Operator, sensors, cables, software, couplant, portable PC	1-10
Calibration	Engineer, operator, portable PC	1-2
Trial period	Operator, portable PC	1-24

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Real-time monitoring	-	e.g. 1 year
Processing	Operator, PC, software	0,2
Validation	Engineer, PC, software	1-3

Table 2.28 – Resources used in FOS technique tasks

2.5.3.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Engineer	hour	7,00	23,21€	162,47€	13,00%	21,12 €	6,00%	9,75 €	193,34 €
Operator	hour	38,20	18,05€	689,51€	13,00%	89,64 €	6,00%	41,37 €	820,52 €
sensors	day	1,00	0,57 €	0,57€	13,00%	0,07 €	6,00%	0,03 €	0,68 €
Cables	day	1,00	0,53 €	0,53€	13,00%	0,07 €	6,00%	0,03 €	0,63 €
Software	day	1,00	4,80 €	4,80€	13,00%	0,62 €	6,00%	0,29 €	5,71 €
Portable PC	day	1,00	45,43€	45,43€	13,00%	5,91 €	6,00%	2,73 €	54,06 €
				903,31€		117,43 €		54,20 €	**1.074,94 €**

Table 2.29 – Breakdown of costs and benefits for the budgeting of FOS technique

2.5.4 Ground Penetrating Radar (GPR)

2.5.4.1 Purpose and main features

GPR allows monitoring of the subsurface and interior of structures such as tunnels and bridges, including their geometry (e.g. deck thickness, reinforcement) and the detection of damage (e.g. moisture, thickness deficiency, corrosion).

For bridges, the GPR method is mainly used to inspect the condition of the deck (and asphalt) and reinforcement bars and, although with more limitations, the piers and foundations. The mobile GPR is placed connected to an external real-time kinematic (RTK) global navigation satellite system (GNSS) for track marking (geo-referenced data) or to a distance measurement indicator (DMI) to monitor the track interval and measure the distance travelled. The system also uses a computer-guided navigation system to correctly follow the profile direction and maintain a constant overlap between parallel profiles without any physical markers on the ground surface.

For tunnels, most GPR work focuses on the assessment of tunnel linings, grouting and reinforcement. The connection to external GPS devices for data referencing is obviously limited when inspecting the interior of a tunnel structure. Therefore, wheel encoders are used during data acquisition in order to ensure the accuracy of the range (tracking interval) and location.

Methods for GPR data analysis include:

- Convolution neural network (CNN)
- Recurrent neural network (RNN)
- Statistical models

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- Image/signal processing methods

Parameters and damages that can be measured with this technique are:

- Cracks: Area (cm^2), depth
- Scale: Area (cm^2), depth
- Holes/cavities: Area (cm^2), depth
- Detachment: Area (cm^2), depth
- Delamination: Longitude (cm) and area (cm2) for 2D and 3D surveys, respectively.
- Deformation: distance from original position (cm)
- Thicknesses: length (cm)
- Moisture: Area (cm^2), depth
- Reinforcement bars: diameter (mm), depth, spacing between bars

2.5.4.2 Scenarios definition

GPR data acquisition can be performed with a single antenna or with an array of antennas offset on the surface of the medium. The first case is common in small, narrow areas or in areas inaccessible to large equipment such as walls or columns. Antenna arrays are used in large unobstructed areas, e.g. for road and pavement inspections.

When possible, and especially for bridge deck inspections, the GPR system operates mounted on a mobile vehicle at the speed of traffic without disturbing normal traffic. The survey of walls or small construction elements is sometimes carried out with transilumination and radar tomography.

In the case of tunnel surveys, additional devices such as hydraulic support systems (mainly a vehicle support with a boom or a hoist) are required to reach the top. In addition, tunnels are usually inspected manually, by manoeuvring the GPR antenna over the surface of the tunnel, with single ground-coupled antennas using the mode of continuous acquisition. In this process, longitudinal survey lines are most commonly arranged, with a range of three to six serial lines located at the vault, the left hance, the right hance, the left sidewall, the right sidewall and the inflected arch.

For data capture at specific elements of the structure, different combinations of antennas will be used:

- Air-launched antennas allow dynamic measurement at traffic speeds. This configuration is most commonly used for monitoring pavements and bridge decks (e.g. thicknesses, cracks, reinforcement bars, etc.).
- Antennas attached to the ground allow dynamic or static measurement. This configuration can be used for monitoring pavements and bridge decks (e.g. thicknesses, cracks, reinforcement bars, etc.), as well as for more local or spot measurements, such as those of piers. Ground-coupled antennas provide a deeper penetration range and better resolution compared to air-coupled antennas.
- Ground-coupled array systems allow for dynamic measurement. This configuration is most commonly focused on pavement and bridge deck monitoring (e.g. 3D rebar mapping, delamination/corrosion mapping, etc.).

The material of construction also influences the performance of the studies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

In general, for materials with a higher dielectric constant (e.g. granite or wet concrete), medium-low frequencies should be used in order to have higher capacity of penetration, although lower resolution, thus compromising the reliability of the data.

In addition, GPR is not applicable to metallic elements and in wet media such as clays or saline or saturated media, the penetration capability of the signal may be reduced by 10 or even lost completely.

The type of infrastructure on which the technique is applied must also be taken into account, as there are certain differences.

On the road, both air-coupled and ground-coupled antennas can be used mounted on a vehicle or on a survey cart. The speed of data collection varies between antennas: air-coupled antennas allow data collection at 80-120 km/h, while ground-coupled antennas operate at 15-20 km/h. The type of road restricts the speed of data collection. Therefore, one or the other will be used depending on the maximum speed of the track type.

In the case of railways, air-coupled antennas are normally used mounted on the train. In railways, the nature of the track elements, ballast and sleepers, are rough contact surfaces for ground-coupled antennas.

Railway GPR monitoring is normally performed along the track, in longitudinal alignments. At least one test profile is measured between the rails, in the track axis.

2.5.4.3 Technology characteristics

GPR systems allow performing digital measurements of different bridge and tunnel structures both automatically and digitally. They also allow dynamic and static measurements, although the most valuable information is provided the first ones.

Through this technique it is possible to carry out a single measure to study the current status of a structure under investigation or monitor the evolution of a structure and/or damage with periodical measurements.

The data shall be stored in binary format files. More information can be found in section 3.3.4.

General system components are listed below:

- Control unit
- Laptop
- Software for data acquisition: depends on the system manufacturer
- Processing software: depends on dimensional data (2D or 3D)
- Antennas:
  - Ground-coupled antennas: surveying cart (optional GPS-RTK) or Platform vehicle (with IMU, GNSS)
  - Air-coupled antennas: Platform vehicle (with IMU, GNSS)

2.5.4.4 Methodology: phases and tasks

Some aspects to be taken into account before applying this technique are:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- The type of soil and its water content. The water content of the soil is strongly determined by the weather conditions and has a large effect on the dielectric permittivity and electrical conductivity of the soil medium.
- Traffic conditions. Air-coupled antennas allow data acquisition at 80-120 km/h, whereas ground-coupled antennas operate at 15-20 km/h. In addition, metal from vehicles can add signal noise to the radar waves.
- Ground-coupled antennas provide data with higher penetration capability and higher resolution (compared to air-coupled antennas).

Data acquisition using this technique should be done in the following steps:

1. Planning: Define profile lines (direction)
2. On-site calibration of the antennas. For both types of antennas it is necessary to calibrate the dielectric properties of the propagation medium (using soundings or CMP) when measuring depths/thicknesses.
3. Capturing: data collection phase. Definition of setting parameters, including,
   - Operating frequency; should provide a good compromise between resolution and depth of penetration.
   - Time window; Time length between two transmitted pulses for which the reflected signals are recorded.
   - Temporal sampling interval; Time interval between points on a recorded waveform; the sampling rate should be approximately six times the centre frequency of the antenna.
   - Spatial sampling interval; this interval should not exceed the Nyquist sampling intervals, which is one quarter of the wavelength in the host medium. Normally, the sampling interval in GPR surveys should be between 50 and 10 scan /m in longitudinal survey profiles.
   - For 3D surveys, configuration of distance between consecutive profiles. In the case of array antennas, the distance is by default. In the case of single air-coupled or ground-coupled antennas, this distance parameter is controlled by the Nyquist sampling concept.
4. Processing: signal filtering to eliminate noise and to amplify signal and visualization techniques. For 3D surveys, use of specific GPR software to create 3D models and time-slices.
5. Validation: interpretation and quantification (damage detection and thickness measurements), accuracy with respect to coring and numerical simulation.

2.5.4.5 Interfaces and Connections

The different components of the GPR systems are connected to each other by cables. Cables are used to connect the antenna to the control unit and to connect the laptop to the central unit.
The acquired data will be stored in binary files that can be transferred to other computers via USB connections or uploaded to repositories or web servers via internet connection and using secure data transfer protocols, such as FTPS.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.4.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.4.6.1 Personnel

Human resource	Cost (€)	Unit
Engineer	38,24	Hour
Operator	26,53	Hour

Table 2.30 – Human resources in GPR technique

2.5.4.6.2 Material resources

Material resource	Cost (€)	Unit
GPR system (control unit + 1 ground-coupled antenna + acquisition software + survey cart + tablet)	1500	Week
Processing software (ReflexW)	1800	Year
GPS (RTK)	150	Day
Coring	600	5 samples

Table 2.31 – Material resources in GPR-simple technique

Material resource	Cost (€)	Unit
GPR array system (control unit + array antennas + acquisition software + monitor)	10000	Week
Processing software (ReflexW/3D or GPR-SLICE)	1800-3000	Year
GPS (RTK)	150	Day
Coring	600	5 samples
Inspection vehicle with coupling and IMU	100	Day

Table 2.32 – Material resources in GPR-array technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

The amortisation price per day of the software used is as follows:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Processing software (ReflexW)	1800	10,00%	2	75,00	11,57€

Table 2.33 – Amortisation of software used in GPR-single technique

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Processing software (ReflexW/3D or GPR-SLICE)	3000	10,00%	2	75,00	19,29 €

Table 2.34 – Amortisation of software used in GPR-array technique

2.5.4.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	Define the proline lines	0,5	Capturing day
	Inspection of the site and selection of potential obstacles /noise sources	0,5	Capturing day
Calibration	Velocity calibration (additional) - coring	1	Capturing day
Capturing	Definition of setting parameters	0,25	Capturing day
	GPR profile lines capture	5	Capturing day
	Adquisition of additional GPS/Topography data	0,5	Capturing day
Processing	Signal processing (2D)	2	Laboratory
	Interpretation	3	Laboratory
Validation	Validation	2	Laboratory

Table 2.35 – Duration of tasks in GPR-single technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Task	Resource	Hours
Define the proline lines	Engineer	0,5
Inspection of the site and selection of potential obstacles /noise sources	Engineer	0,5
Velocity calibration (additional)	Engineer, Operator, GPR system, Coring	1
Definition of setting parameters	Engineer, GPR system	0,25
GPR profile lines capture	Operator, GPR system	5
Adquisition of additional GPS/Topography data	Operator, GPS	0,5
Signal processing (2D)	Engineer, Processing software, Standard computer	2
Interpretation	Engineer, Standard computer	3
Validation	Engineer, Standard computer	2

Table 2.36 – Resources used in GPR-single technique tasks

Phase	Task	Duration (hours)	Unit
Planning	Define the proline lines	0,5	Capturing day
	Inspection of the site and selection of potential obstacles /noise sources	0,5	Capturing day
Calibration	Velocity calibration (additional) - coring	1	Capturing day
Capturing	Definition of setting parameters	0,25	Capturing day
	GPR profile lines capture	2	Capturing day
	Adquisition of additional GPS/Topography data	0,2	Capturing day
Processing	Signal processing (3D)	3	Laboratory
	Interpretation	2	Laboratory
Validation	Validation	3	Laboratory

Table 2.37 – Duration of tasks in GPR-array technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Task	Resource	Hours
Define the proline lines	Engineer	0,5
Inspection of the site and selection of potential obstacles /noise sources	Engineer	0,5
Velocity calibration (additional)	Engineer, Operator, GPR array system, Coring	1
Definition of setting parameters	Engineer, GPR array system, vehicle	0,25
GPR profile lines capture	Operator, GPR array system, vehicle	2
Adquisition of additional GPS/Topography data	Operator, GPS	0,2
Signal processing (2D)	Engineer, Processing software, Standard computer	3
Interpretation	Engineer, Standard computer	2
Validation	Engineer, Standard computer	3

Table 2.38 – Resources used in GPR-array technique tasks

2.5.4.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Engineer	hour	9,25	38,24	353,72€	13,00%	45,98 €	6,00%	21,22 €	420,93 €
Operator	hour	6,5	26,53	172,45€	13,00%	22,42 €	6,00%	10,35 €	205,21 €
GPR system	day	1	300	300,00€	13,00%	39,00 €	6,00%	18,00 €	357,00 €
Coring	sample	5	120	600,00€	13,00%	78,00 €	6,00%	36,00 €	714,00 €
GPS	day	1	150	150,00€	13,00%	19,50 €	6,00%	9,00 €	178,50 €
Processing software	day	1	11,57	11,57€	13,00%	1,50 €	6,00%	0,69 €	13,77 €
				1.587,74 €		206,41 €		95,26€	**1.889,40€**

Table 2.39 – Breakdown of costs and benefits for the budgeting of GPR-simple technique

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Engineer	hour	10,25	38,24	391,96€	13,00%	50,95 €	6,00%	23,52 €	466,43 €
Operator	hour	6,5	26,53	172,45€	13,00%	22,42 €	6,00%	10,35 €	205,21 €
GPR array system	day	1	2000	2.000,00 €	13,00%	260,00 €	6,00%	120,00 €	2.380,00 €
Coring	sample	5	120	600,00€	13,00%	78,00 €	6,00%	36,00 €	714,00 €
GPS	day	1	150	150,00€	13,00%	19,50 €	6,00%	9,00 €	178,50 €

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Processing software	day	1	19,29	19,29€	13,00%	2,51 €	6,00%	1,16 €	22,96 €
vehicle	day	1	100	100,00€	13,00%	13,00 €	6,00%	6,00 €	119,00 €
				3.433,70 €		446,38 €		206,02€	**4.086,10€**

Table 2.40 – Breakdown of costs and benefits for the budgeting of GPR-array technique

2.5.5 Guided Waves Propagation (GW)

2.5.5.1 Purpose and main features

Guided wave propagation surveying is a promising and non-destructive test for damage detection and monitoring of the structural condition of infrastructures, as well as their maintenance.

This technology targets complete structures, as waves excited at one end of the structure propagate through the volume and waveforms can be recorded on site.

However, there are several types of methods:
- Impact-Echo test
- Ultrasonic Pulse Velocity Test
- Spectral Analysis of Surface Waves,

and the first of these can be used for: slabs, beams, columns, walls, pavements, runways and dams.

Some of the parameters and structural damage that can be measured in bridges and tunnels with guided waves propagation are:
- Freeze-thaw damage depth measurement
- Fire damage depth measurement
- Surface cracks depth
- Compressive strength
- Detection of voids, imperfections
- Velocity vs. strength correlation with cores

2.5.5.2 Scenarios definition

The application of this technology does not differ according to the type of structure or element on which the study is carried out, the material from which it is constructed or the type of infrastructure in which it is located.

2.5.5.3 Technology characteristics

Guided wave propagation technology allows digital measurements in a automatic and static way of different structural damages.

It is possible to carry out several measurements at the same time or several measures in a specific period of time, which will be stored in files and databases.

The equipment required to apply this technique is composed of:
- Ultrasonic pulse velocity tester
- Impact-echo testing equipment
- Spectral Surface Wave Analysis testing equipment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

These elements can be applied in structures of different materials, such as concrete, steel, glass fibers, polymers, and composites.

2.5.5.4 Methodology: phases and tasks

One thing to note is that the wave must propagate in a spiral. This is a necessary condition so that the different types of reflected waves do not disturb the measurement and the attenuation along the path is small enough to be able to record the return wave.

For the implementation of the technology, the following steps have to be distinguished:

1. Planning
2. Calibration
3. Capture of
4. Processing
5. Analysis

2.5.5.5 Interfaces and Connections

The test equipment used in this technique does not require connection to any other components. The collected graphical data shall be stored in files which can be stored in a database or displayed on screen. Therefore, a user interface implementing services for data management is needed to allow the visualisation of the data. In addition, the services must allow users to add new data to the database and to manage them.

2.5.5.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.5.6.1 Personnel

Human resource	Cost (€)	Unit
Bridge Inspector	23,21	Hour

Table 2.41 – Human resources for GW technique

2.5.5.6.2 Material resources

Material resource	Cost (€)	Unit
Ultrasonic pulse velocity tester for concrete	2441,74 - 3165,22	Device
Impact-echo testing equipment for concrete	5426,10	Device
Spectral Surface Wave Analysis testing equipment	4000	Device

Table 2.42 – Material resources for GW technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

The depreciation value of each device is calculated on the basis of its purchase price:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Ultrasonic pulse velocity tester for concrete	3165€	10,00%	3	100,00	9,50€
Impact-echo testing equipment for concrete	5426,1€	10,00%	3	100,00	16,28€
Spectral Surface Wave Analysis testing equipment	4000€	10,00%	3	100,00	12,00€

Table 2.43 – Amortisation of materials used in GW technique

2.5.5.6.3 Performance

Phase	Task	Duration (hours)	Unit
Inspection preparation	Situational sketch of the bridge under studies	1-2	Bridge
	Marking the elements to be controlled	1-2	Bridge
	Checking the historical documentation of the bridge	1-2	Bridge
	Checking the results of last inspection	1	Bridge
Preparation	Range Selection for the pulse velocity	0,2	-
	Measurement of the path length	0,2	-
	Checking the instrument zero with a reference bar is provided	0,5	-
Measurement	Measurement of the pulse velocity	0,5	-
Reporting	Data interpretation and conclusions	0,5-1	-

Table 2.44 – Duration of tasks in GW technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Task	Resource	Hours
Situational sketch of the bridge under studies	Bridge Inspector	1-2
Marking the elements to be controlled	Bridge Inspector	1-2
Checking the historical documentation of the bridge	Bridge Inspector	1-2
Checking the results of last inspection	Bridge Inspector	1
Range Selection for the pulse velocity	Bridge Inspector, Ultrasonic pulse velocity tester	0,2
Measurement of the path length	Bridge Inspector, Ultrasonic pulse velocity tester	0,2
Checking the instrument zero with a reference bar is provided	Bridge Inspector, Ultrasonic pulse velocity tester	0,5
Measurement of the pulse velocity	Bridge Inspector, Ultrasonic pulse velocity tester	0,5
Data interpretation and conclusions	Bridge Inspector	0,5-1

Table 2.45 – Resources used in GW technique tasks

2.5.5.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/ Unit	Cost	%O	O	% B	B	Budget
Bridge inspector	hor	10,40	23,21	241,38€	13,00%	31,38 €	6,00%	14,48 €	287,25 €
Ultrasonic pulse velocity tester for concrete	day	1,00	9,50 €	9,50€	13,00%	1,24 €	6,00%	0,57 €	11,31 €
Impact-echo testing equipment for concrete	day	1,00	16,28 €	16,28 €	13,00%	2,12 €	6,00%	0,98 €	19,37 €
Spectral Surface Wave Analysis testing equipment	day	1,00	12,00 €	12,00 €	13,00%	1,56 €	6,00%	0,72 €	14,28 €
				279,16€		36,29€		16,75 €	**332,21€**

Table 2.46 – Breakdown of costs and benefits for the budgeting of GW technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.6 Light or Laser Imaging Detection And Ranging (LIDAR)

2.5.6.1 Purpose and main features

LiDAR is a surveying technique aimed at sampling the surface of the target object, providing the so-called 3D Point cloud for the inspection of infrastructure assets. If surveys are carried out periodically, the 3D model supports infrastructure monitoring through multi-epoch change detection.

LiDAR and surface monitoring is applicable to bridge and tunnel structure as a whole. Nevertheless, 3D Point clouds and models can be postprocessed to perform data analysis at component and object levels.

LiDAR is frequently used with other sensors to complete the surveying:

- GNSS surveying. Global georeferencing of LiDAR data is based on GNSS. In addition, terrestrial laser scanner (TLS) can exploit information from location to improve data registration from different points of view, the so-called scan-positions. MLS needs for a navigation solution to register and obtain final data.
- Inertial Measurement Units (IMUs) provide a solution for navigation (Inertial Navigation Systems, INS) based on a Dead Reckoning process. IMUs are essential in mobile laser scanner (MLS) to obtain the orientation of the sensor and complete data georeferencing.

Methods for LiDAR data analysis include:

- Statistical Methods

- Convolutional Neural Networks (CNN)

Through this technique is possible to obtain the value of several parameters ato represent some structural damages. They are listed below:

- Cracks: Area (cm^2)
- Scaling: Area (cm^2)
- Holes: Area (cm^2), depth
- Displacements: longitude (cm)
- Loss of section: Volume (cm^3)
- Deformation: separation from the original position (cm)
- Break: distance from the beginning of the cable (cm)
- Bending: Angle (º)
- Rupture: distance from the beginning of the stirrup (cm)

2.5.6.2 Scenarios definition

Different laser scanning systems and platforms can be used depending on the structure on which the technique is applied. For more accurate and precise surveying, TLS is a preferred option, providing very dense data about components and objects in the infrastructure. The drawback of this technique consists of longer time for data acquisition in the field.

For a more productive surveying, the use of terrestrial mobile platforms such as backpacks or, more often, cars or vans is the state-of-the-art technique. Surveying is performed at travelling

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

speeds without disturbing the traffic. The precision and accuracy of data are limited by the solution of mobile navigation. This is crucial for tunnels, where the navigation largely depends on Dead Reckoning solutions subject to drift it. This is also the reason why applicability of UAV-based LiDAR to tunnels is very limited. Due to more obvious reasons, ALS is only applicable to bridges.

The infrastructure required for the survey does not depend on the elements of the structure, as laser scanning systems record the entire structure in a single survey. Depending on the visibility of the component or element of the asset, the platform used to carry out the surveying should be carefully selected taking into account the point-of-view of the sensor. For lower height, terrestrial platforms should be considered whilst UAV based inspection is adequate for areas with a difficult access.

In general, the materials of the elements of the structure do not affect the surveying procedure but the reliability of the data. However, LiDAR is not applicable for transparent (e.g., glass) or specular (metal) materials , because the measurements obtained are noisy due to their reflectivity. Taking into account the nature of the material is very important, especially, at planning phase.

Depending on the selected platform for surveying, accessibility to the asset may be limited due to environmental and administrative restrictions, especially in railway environment. For terrestrial platforms, the vehicle to carry MLS differs depending on the environment. In road, the equipment is placed on a car/van while in railway, it can be placed on car/van or on a train. Furthermore, environment type must be taken into account because of the requirements and constraints the infrastructure imposes on MLS, especially, for the definition of the trajectory of the system.

Therefore, the main differences in laser scanning performance are determined by the vehicle used in MLS and the platform on which the sensor is mounted (van, train, UAV, aircraft, etc.), as this will determine the productivity of the scanning.

2.5.6.3 Technology characteristics

LIDAR technologies allow digital measurements of the scanned environment to be obtained automatically. This scanning can be performed in static or moving mode, for which TLS and MLS will be used respectively.

With this technique it is possible to take a single measurement to study the current state of a structure or several periodically ones to monitor the evolution of a structure over time.

Regarding what was explained in the previous section, the definition of the different scanning technologies to be considered (static and mobile) will depend on the considered scenarios:

- Static scanning involves the use of sensors that do not change their position during a scanning operation, either ground-based on tripods (such as terrestrial laser scanners or thermal imaging cameras) or mounted on roadway elements (usually fixed, such as surveillance cameras).

  A typical static scanning operation involves the use of a terrestrial laser scanner (TLS) capable of taking point clouds using LIDAR technology and imagery, positioned using a GNSS antenna. These devices are autonomous in acquiring the cloud points from the surrounding environment, so it only needs to be moved to all the necessary points to reach all the space required.

- Mobile scanning systems are installed in vehicles relatively adapted to the sensors used (more so in the case of railway scanning) and are capable of covering a large

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

number of kilometres in a short time, the accuracy being relative to the speed of capture.

Land mobile scanning vehicles are typically equipped with at least one or two LIDAR scanners, an inertial measurement unit (IMU) with one or two antennas for GNSS positioning and a distance measuring instrument (DMI) for detection of the forward speed, and a 360° camera for panoramic imaging.

Due to being in motion, positioning the vehicle accurately is the most delicate part of the process. The accuracy of satellite positioning is often improved through the use of fixed GNSS bases and control points along the trajectory.

Therefore, the common components in both devices are the LiDAR sensor, a high-performance computer, the recording software, the storage hardware and the processing software. In the case of TLS, a tripod and a tablet will also be required. For MLS, the platform vehicle, an IMU and GNSS.

The registration software requirements are different for TLS and MLS, and typically constrained by the system manufacturer. Point cloud georeferencing in MLS requires the trajectory followed by the vehicle because the point cloud is registered to the Position and Orientation (POSE) of the vehicle during the surveying.

The following table summarises the components of both equipment:

EQUIPMENT	POSITIONING	LiDAR	IMAGING
MMS_1	**IMU (Inertial Measurement Unit)** - 3 MEMS gyros: bias instability < 0.5 °/h, noise < 0.15 °/√h - 3 accels: input range ±5g, bias instability 0.05mg - 3 inclinometers **DMI (Distance Measurement Instrument)** - Resolution: ≥ 5000 pulses/rev - Direction detection - Protection: IP67 **GNSS antenna** - Support for GPS, GLONASS, Galileo, BeiDou and SBAS - Signal gain: ≥ 50 dB	**2 sensors** - Max. measuring range: > 200 m - Max rate: 1,000,000 points/s - Accuracy: 5 mm - Field of view: 360° - Scan speed: 250 rev/s - Max. Laser Pulse Rate: > 500 kHz	**6 cameras** 360° RGB sensor (6 30 mpx cameras) with NMEA and PPS inputs
TLS_1	Dual axis compensator: ± 5° Height sensor Compass Integrated GPS receiver	- Max. measuring range: > 200 m - Max rate: 1,000,000 points/s - Accuracy: 2 mm - Field of view: 360°	165 mpx

Table 2.47 – Equipment components for LIDAR technologies

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.6.4 Methodology: phases and tasks

There are some aspects to consider when applying MLS and TLS technologies:

Survey planning is of utmost importance to obtain adequate point clouds in terms of accuracy, coverage and point density. The density of point clouds in the MLS is higher when the survey vehicle moves slower.

Weather conditions should also be taken into account, as they affect the reliability of the measurements. Data capture shall be avoided on rainy or foggy days, as droplets will cause noise in the point clouds that will invalidate them.

In addition, it is important to take traffic conditions into account, as denser is the traffic, the larger and more frequent the occlusions in the point cloud will be.

The phases common to the use of both technologies are outlined below:

1. Planning: Define assets to survey, path planning for mobile platforms and different scan-positions for the scanner in TLS.
2. Calibration: Laboratory calibration of intrinsic parameters and experimental calibration of extrinsic parameters.
3. Capturing: data collection phase. Definition of the key parameters for the surveying, including:
    - Data capturing rate: acquisition rate; it is usually measured in frequency (i.e. kHz or MHz)
    - Point density: depends on the angular step between consecutive measurements and, in addition, the speed of the platform for MLS/ALS.
    - Distance range: There is a trade-off between the maximum range to be measured with a LiDAR and the number of effective measurements rate (EMR). The higher the LiDAR speed the shorter the maximum range to be measured.
    - Need for radiometric information, that would include the need for capturing images from cameras (optical sensors)
    - For MLS, UAV-based or ALS, capturing the trajectory followed by the mobile platform with GNSS/INS navigation systems. The optimization of the trajectory to improve precision of the data imposes also requirements for the data collection.
4. Processing: effectively generate point clouds from raw measurements. This process may be different for TLS or MLS point clouds, being point cloud registration the critical step.
5. Validation: Quantification of point clouds density, accuracy and/or precision with respect to reference control points and measurements.

The tasks distinguished within each phase may be different for MLS and TLS. In the following, the two cases are differentiated:

- **TLS:**

1. Planning
    - Identification of asset access
    - Checking meteorological conditions for the day of the survey
    - Measurement points establishment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2. Calibration:
   - Radiometric calibration of the sensors
3. Capturing:
   - Initialization and creation of survey project/scan
   - Levelling
   - Definition of field of view
   - Definition of point cloud density (or acquisition rate)
   - Point cloud capture
4. Processing:
   - Point cloud registration (by setting correspondences between control/tie points)
   - Exportation of the consolidated point cloud to standard formats
5. Validation:
   - Validation

- **MLS:**

1. Planning:
   - Identification of asset access
   - Checking meteorological conditions for the day of the survey
   - Path planning and prevision of GNSS coverage during the day/time of acquisition
2. Calibration:
   - Boresighting of the different sensors involved (geometric calibration)
   - Radiometric calibration of the sensors
3. Capturing:
   - Initialization and creation of survey project
   - Definition of surveying parameters (acquisition rate, trajectory acquisition rate, maximum range)
   - Point cloud capture
4. Processing:
   - Reconstruction and filtering of trajectory data
   - Synchronization of the filtered trajectory and the raw LiDAR data
   - Exportation of the consolidated point cloud to standard formats
5. Validation:
   - Validation

2.5.6.5 Interfaces and Connections

The systems are formed by several components, both hardware and software, interconnected in a proper way to ensure communications.

On the one hand, the acquisition equipment must be integrated with the positioning system, the GNSS antenna and the control unit, which can be a PC or a tablet. These connections can be via cable or via Wi-Fi.

It is also necessary to connect the equipment to the storage medium, via USB.

The transmission of the generated data can be done manually or remotely. In the first case, the workers will manage the data and upload them to the file repositories by connecting the storage device to the PC via USB.

In the case of remote uploading, it will be necessary to use a protocol to transfer the data from the PC to the web server, such as TCP/IP or FTSP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.6.6 Resources

The recommended scanning technologies and some proposed sensors are presented, in order to compare the costs of the different solutions according to the required use.

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.6.6.1 Personnel

Human resource	Cost (€)	Unit
Engineer	38,24	Hour
Operator	26,53	Hour

Table 2.48 – Human resources for LIDAR technologies

2.5.6.6.2 Material resources

- **MLS**

Material resource	Cost (€)	Unit
LiDAR sensor (+ 5% insurance)	3.240	Day
Vehicle	80	Day
Storage hardware	0,05	GB
High performance computer	12	Day
Registration software	1300	Week
Processing software	1400	Week

Table 2.49 – Material resources for MLS technology

- **TLS**

Material resource	Cost (€)	Unit
LiDAR sensor (+ 5% insurance)	415	Day
Tablet (+ 5% insurance)	32	Day
Storage hardware	0,05	GB
High performance computer	12	Day
Registration software	175	Week
Processing software	180	Week

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table 2.50 – Material resources for TLS technology

The elements are not bought, so there are no amortisation costs calculated.

2.5.6.6.3 Performance

- **MLS**

Phase	Task	Duration (hours)	Unit
Planning	Identification of asset access	1	Capturing day
	Path planning and prevision of GNSS coverage	1	Capturing day
	Path planning and prevision of GNSS coverage during the day/time of acquisition	4	Capturing day
Calibration	Boresighting of the different sensors involved	0,5	Capturing day
	Radiometric calibration of the sensors	0,5	Capturing day
Capturing	Initialization and creation of survey project	0,25	Capturing day
	Definition of surveying parameters	0,25	Capturing day
	Point cloud capture	6,5	Capturing day
Processing	Reconstruction and filtering of trajectory data	2	Capturing day
	Synchronization of the filtered trajectory and the raw LiDAR data	1	Capturing day
	Exportation of the consolidated point cloud to standard formats	1	Capturing day
Validation	Validation	1	Capturing day

Table 2.51 – Duration of tasks in MLS technology

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Task	Resource	Hours
Identification of asset access	Engineer, High performance computer	1
Path planning and prevision of GNSS coverage	Engineer, High performance computer	1
Path planning and prevision of GNSS coverage during the day/time of acquisition	Engineer, High performance computer	4
Boresighting of the different sensors involved	Operator, LiDAR sensor, Vehicle	0,5
Radiometric calibration of the sensors	Engineer, High performance computer	0,5
Initialization and creation of survey project	Engineer, High performance computer	0,25
Definition of surveying parameters	Engineer, High performance computer	0,25
Point cloud capture	Operator, LiDAR Sensor, Vehicle, High performance computer, Storage hardware, Registration software	6,5
Reconstruction and filtering of trajectory data	Engineer, High performance computer, Storage hardware, Processing software	2
Synchronization of the filtered trajectory and the raw LiDAR data	Engineer, High performance computer, Storage hardware, Processing software	1
Exportation of the consolidated point cloud to standard formats	Engineer, High performance computer, Storage hardware	1
Validation	Engineer, High performance computer	1

Table 2.52 – Resources used in MLS technology tasks

- **TLS**

Phase	Task	Duration (hours)	Unit
Planning	Identification of asset access	0,5	Capturing day
	Checking metheorological conditions	0,5	Capturing day

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	Measurement points establishment	2	Capturing day
Calibration	Radiometric calibration	1	Capturing day
Capturing	Initialization and creation of survey project /scan	0,25	Capturing day
	Levelling	0,25	Capturing day
	Definition of field of view	0,25	Capturing day
	Definition of point cloud density (or acquisition rate)	0,25	Capturing day
	Point cloud capture	7	Capturing day
Processing	Point cloud registration	3	Capturing day
	Exportation of the consolidated point cloud	1	Capturing day
Validation	Validation	1	Capturing day

Table 2.53 – Duration of tasks in TLS technology

Task	Resource	Hours
Identification of asset access	Engineer, High performance computer	0,5
Checking metheorological conditions	Engineer, High performance computer	0,5
Measurement points establishment	Engineer, High performance computer	2
Radiometric calibration	Engineer, LiDAR sensor & Tripod, Tablet	1
Initialization and creation of survey project /scan	Operator, Tablet, Registration software	0,25
Levelling	Operator, Tablet, Registration software	0,25
Definition of field of view	Operator, Tablet, Registration software	0,25
Definition of point cloud density (or acquisition rate)	Operator, Tablet, Registration software	0,25

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Point cloud capture	Operator, LiDAR sensor & Tripod, Tablet, Storage hardware, Registration software	7
Point cloud registration	Engineer, High performance computer, Storage hardware, Registration software	3
Exportation of the consolidated point cloud	Engineer, High performance computer, Storage hardware, Processing software	1
Validation	Engineer, High performance computer, Storage hardware, Registration software	1

Table 2.54 – Resources used in TLS technology tasks

2.5.6.6.4 Cost/benefit analysis

- **MLS**

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Engineer	hour	12,00	38,24 €	458,88€	13,00%	59,65 €	6,00%	27,53 €	546,07 €
Operator	hour	7,00	26,53 €	185,71€	13,00%	24,14 €	6,00%	11,14 €	220,99 €
High performance computer	day	1,00	12,00€	12,00€	13,00%	1,56 €	6,00%	0,72 €	14,28 €
LiDAR sensor	day	1,00	3.240,00 €	3.240,00 €	13,00%	421,20 €	6,00%	194,40 €	3.855,60 €
Vehicle	day	1,00	80,00€	80,00€	13,00%	10,40 €	6,00%	4,80 €	95,20 €
Storage hardware	GB	50,00	0,05€	2,50€	13,00%	0,33 €	6,00%	0,15 €	2,98 €
Registration software	day	1,00	260,00€	260,00€	13,00%	33,80 €	6,00%	15,60 €	309,40 €
Processing software	day	1,00	280,00€	280,00€	13,00%	36,40 €	6,00%	16,80 €	333,20 €
				4.519,09 €		587,48 €		271,15€	**5.377,72€**

Table 2.55 – Breakdown of costs and benefits for the budgeting of the MLS technology

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- **TLS**

Resource	Unit	Units	Cost/ Unit	Cost	%O	O	% B	B	Budget
Engineer	hour	9,00	38,24 €	344,16 €	13,00%	44,74 €	6,00%	20,65 €	409,55 €
Operator	hour	8,00	26,53 €	212,24 €	13,00%	27,59 €	6,00%	12,73 €	252,57 €
High performance computer	day	1,00	12,00€	12,00€	13,00%	1,56 €	6,00%	0,72 €	14,28 €
LiDAR sensor	day	1,00	415	415,00 €	13,00%	53,95 €	6,00%	24,90 €	493,85 €
Tablet	day	1,00	32,00€	32,00€	13,00%	4,16 €	6,00%	1,92 €	38,08 €
Storage hardware	GB	50,00	0,05€	2,50€	13,00%	0,33 €	6,00%	0,15 €	2,98 €
Registration software	day	1,00	35,00€	35,00€	13,00%	4,55 €	6,00%	2,10 €	41,65 €
Processing software	day	1,00	36,00€	36,00€	13,00%	4,68 €	6,00%	2,16 €	42,84 €
				1.088,90€		141,56€		65,33 €	**1.295,79 €**

Table 2.56 – Breakdown of costs and benefits for the budgeting of the TLS technology

2.5.7 Magnetic and Electrical Methods (MEM)

2.5.7.1 Purpose and main features

Electromagnetic methods have been widely used in bridges and tunnels maintenance, especially for the detection of corrosion in post-tensioned concrete elements.

This technology can be applied to different infrastructure elements, such as girders, columns, bridge slabs, reinforced walls, concrete slab soffits, retaining walls or welded joints.

It is also possible to use different sensors. The most common ones are mentioned below:

- Electromagnetic Pulse Induction Methods
- Magnetic Memory Method (MMM)
- Magnetic Flux Leakage Method (MFL)
- Pulsed Eddy Current Response (PEC)

In the case of bridge infrastructure management, the most commonly used techniques are based on electromagnetic pulse induction technology. The magnetic flux leakage method can also be used in structural health monitoring.

Structural defects, representative of damage, that can be determined by electromagnetic methods are:

- Cracks
- Corrosion of the reinforcement bars
- Loss of section

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- Reinforcement bar failure
- Bending (the diameter of cover [mm]; diameter of rebar [mm])

2.5.7.2 Scenarios definition

As in the case of other technologies, there are no differences in its application depending on the type of structure or element on which the study is carried out, the material with which it is built or the type of infrastructure in which it is located.

2.5.7.3 Technology characteristics

The use of magnetic and electrical methods allows automatic and static digital measurements to be obtained. It is possible to take one or several measurements at the same time. Even several measurements in a specific period of time.

The corrosion maps obtained as a result will have numerical and graphical information that will be stored in files on a storage medium and can be displayed on a screen.

The instrumentation required to apply this technique depends on the sensor used. However, in all cases a covermeter is needed. In the case of the Magnetic Memory Method, a powerful magnet and a magnetic detector are also needed.

2.5.7.4 Methodology: phases and tasks

It is important to note that MFL equipment is generally not intrinsically safe and should not be operated in a potentially explosive environment.

In addition, they generate strong magnetic fields and may present some risks to operators and electronic equipment. There can be a significant difference in the performance of persons performing any MFL inspection.

Due to the complexity of the methods, it is not easy to establish a specific procedure. Depends on the structure of understudies and the type of method used. However, some common steps and tasks can be indicated:

Detailed technical sketches should be prepared prior to the measurement. All information about the surveyed area, environmental conditions and expected results should be documented.

1. Preparation
    - Documentation of information about the surveyed area, environmental conditions and expected results.
    - Calibration (periodical)
    - Component of measurement uncertainty estimation
    - Initialisation
    - Post-installation verification
2. Data acquisition

2.5.7.5 Interfaces and Connections

The sensors used in the different methods must be connected to a coverage meter, which will be done via Wi-Fi.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

The numerical and graphical values resulting from the measurements will be stored on some storage medium in files of a suitable format. This will be done through a USB, Wi-Fi or Bluetooth connection. To enable their visualisation, a user interface is needed that implements services for data management that allow the modification and visualisation of the data.

2.5.7.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.7.6.1 Personnel

Human resource	Cost (€)	Unit
Bridge Inspector	23,21	Hour

Table 2.57 – Human resources for MEM methods

2.5.7.6.2 Material resources

Material resource	Cost (€)	Unit
Magnetic Memory Method equipment	7000,76	Device
Magnetic Flux Leakage equipment	7323,76	Device
Pulsed Eddy Current testing set	6408,29	Device

Table 2.58 – Material resources for MEM methods

The amortisation cost per day of the material used is as follows:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Magnetic Memory Method equipment	7000,76€	10,00%	3	100,00	21,00€
Magnetic Flux Leakage equipment	7323,76€	10,00%	3	100,00	21,97€
Pulsed Eddy Current testing set	6408,29€	10,00%	3	100,00	19,22€

Table 2.59 – Amortisation of materials used in MEM methods

2.5.7.6.3 Performance

Phase	Task	Duration (hours)	Unit
Preparation for Inspection Work	Situational sketch of the bridge to be inspected	1	Bridge
	Elements to be checked	1	Bridge
Preparation of the equipment	Setup of base line and scanning line	1	Bridge

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	Preparation of concrete surface	1-5	Bridge
	Inspection of the testing device	0,5	-
Measurement	Measurements and range of scanning	1-5	Per one inspection point
	Location of rebars	1	Per one inspection point
	Measuring rebars diameter	0,5	Per one inspection point
	In-plane location of rebar	0,5	Per one inspection point
Reporting	Documentation of the inspection	1-3	Bridge

Table 2.60 – Duration of tasks in MEM methods

Task	Resource	Hours
Situational sketch of the bridge to be inspected	Bridge Inspector	1
Elements to be checked	Bridge Inspector	1
Setup of base line and scanning line	Bridge Inspector	1
Preparation of concrete surface	Bridge Inspector	1-5
Inspection of the testing device	Bridge Inspector	0,5
Measurements and range of scanning	Bridge Inspector	1-5
Location of rebars	Bridge Inspector	1
Measuring rebars diameter	Bridge Inspector	0,5
In-plane location of rebar	Bridge Inspector	0,5
Documentation of the inspection	Bridge Inspector	1-3

Table 2.61 – Resources used in MEM methods tasks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.7.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Bridge inspector	hour	18,50	23,21 €	429,39€	13,00%	55,82 €	6,00%	25,76 €	510,97 €
Magnetic Memory Method equipment	day	1,00	21,00 €	21,00€	13,00%	2,73 €	6,00%	1,26 €	24,99 €
Magnetic Flux Leakage equipment	day	1,00	21,97 €	21,97€	13,00%	2,86 €	6,00%	1,32 €	26,14 €
Pulsed Eddy Current testing set	day	1,00	19,22 €	19,22€	13,00%	2,50 €	6,00%	1,15 €	22,87 €
				491,58€		63,90€		29,49€	**584,97€**

Table 2.62 – Breakdown of costs and benefits for the budgeting of the MEM methods

2.5.8 Mechanical Test on Cored Samples

2.5.8.1 Purpose and main features

Mechanical testing is a type of destructive technology used for bridges or tunnels maintenance. They must be performed as part of the inspection in the life cycle of the object and are often used on hardened concrete for the characterisation of its properties, such as compressive strength, which will affect the durability of the different structural elements of bridges or tunnels.

This technique can be applied to different elements of the structure such as steel-concrete spans, concrete bridge supports, abutments, bearings and pillars.

In addition, there are different methods that can be employed. They are the following:

- Compressive strength test
- Fatigue test
- Torque test
- Tensile tests
- Abrasion resistance test

Through these methods it is possible to determine the following parameters and structural damage:

- Cracks:
  - fatigue cracks (depth, width)
  - transverse cracks(depth, width)
- Compression resistance: maximum load [N] at which failure of the sample has been registered.
- Fatigue: force [N] needed to break the sample over a number of cycles of stress.
- Torque: maximum torque/rotational force resisted by the material; tension force in the bolt or screw as a function of the applied torque moment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- Tensile: force [N] needed to break the sample under load.
- Abrasion resistance: average loss in mass [g] or depth of wear [mm]

2.5.8.2 Scenarios definition

When applying this technology it should be noted that, depending on the part of the structure from which the samples have been collected, their preparation may vary.

It will also depend on the type of infrastructure material, as although the application of the machines used may not change, some adjustments have to be made because the mechanical properties will be different for a specific material.

As for the environment in which the structure is located (railway or different types of roads), this will not make any difference when carrying out the study, since the tests are carried out in the laboratory.

2.5.8.3 Technology characteristics

The use of this technique allows both mechanical and digital static measurements to be obtained. Both manual and automatic measurements are possible, and unlike other technologies, only one numerical measurement is obtained each time it is applied.

The equipment required includes the following instruments:

- Core drill for obtaining cylindrical core specimens
- Shot drill: for specimens to be removed by drilling downward perpendicular to a horizontal surface
- Diamond drill: for specimens taken by drilling in other directions or when the test specimen diameter is to be determined for more precise calculation of compressive strength
- Calipering device, to measure the length of axial elements of the core
- Scale
- Rotating-cutter machine
- Universal testing machine

2.5.8.4 Methodology: phases and tasks

Since mechanical tests on cored samples are performed under controlled environmental conditions, no significant factors should influence the measurements.

The steps to be carried out for the application of this technique are listed below:

1. Preparation of the samples for further testing in the laboratory
2. Calibration processes
3. Performance of the measurement
4. Documentation of the results and observation
5. Validation of results
6. Conclusions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.8.5 Interfaces and Connections

The testing process is carried out manually without the use of electronic devices. For this reason, the definition of interfaces and connections is limited in this case to the definition of a user interface and its related services. The implementation must take into account the following features:

- The software may be allocated on a local medium such as a computer or hosted on a cloud server.

It is needed an user interface which implements services for managing the data allowing the data modification and visualization.

2.5.8.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.8.6.1 Personnel

Human resource	Cost (€)	Unit
Bridge Inspector	23,21	Hour

Table 2.63 – Human resources for Mechanical Test on Cored Samples

2.5.8.6.2 Material resources

Material resource	Cost (€)	Unit
Electronic stress/mechanical test machine	11378,85	Device
Abrasion Resistance Testing Machine	915,14	Device
Drill	392,68	Device

Table 2.64 – Material resources for Mechanical Test on Cored Samples

The amortisation cost per day of the material used is as follows:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Electronic stress/mechanical test machine	11378,85€	10,00%	3	100,00	34,14€
Abrasion Resistance Testing Machine	915,14€	10,00%	3	100,00	2,75€
Drill	392,68€	10,00%	3	100,00	1,18€

Table 2.65 – Amortisation of materials used in Mechanical Test on Cored Samples

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.8.6.3 Performance

Phase	Task	Duration (hours)	Unit
Preparation (on-site)	Collection of the drilled cores	1-8	Bridge
Calibration (laboratory)	Calibration of the testing machine	0,5	One round of testing
Initialization (laboratory)	Setting the test parameters on the machine	0,5	One round of testing
Measurement	Start of the test	5 minutes	Depends on the type of testing parameters
Reporting	Generation of the report	1 minutes	Per sample

Table 2.66 – Duration of tasks in Mechanical Test on Cored Samples

Task	Resource	Hours
Collection of the drilled cores	Bridge Inspector, drill	1-8
Calibration of the testing machine	Bridge Inspector, testing machine	0,5
Setting the test parameters on the machine	Bridge Inspector, testing machine	0,5
Start of the test	Bridge Inspector, testing machine	5 minutes
Generation of the report	Bridge Inspector, testing machine	1 minutes

Table 2.67 – Rsources used in Mechanical Test on Cored Samples tasks

2.5.8.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Bridge inspector	hour	9,00	23,21 €	208,89€	13,00%	27,16 €	6,00%	12,53 €	248,58 €
Electronic stress/mechanical test machine	day	1,00	34,14 €	34,14€	13,00%	4,44 €	6,00%	2,05 €	40,63 €
Abrasion Resistance Testing Machine	day	1,00	2,75 €	2,75€	13,00%	0,36 €	6,00%	0,17 €	3,27 €

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Drill	day	1,00	1,18 €	1,18€	13,00%	0,15 €	6,00%	0,07 €	1,40 €
				246,96€		32,10€		14,82€	**293,88€**

Table 2.68 – Breakdown of costs and benefits for the budgeting of the Mechanical Test on Cored Samples

2.5.9 Micro Electro-Mechanical Systems (MEMS) - Accelerometers

2.5.9.1 Purpose and main features

Micro electro-mechanical systems allow the infrastructure management for bridges monitoring, as well as maintenance and safety works. Thanks mainly to its cost, it is used for dense sensing (monitoring system with a large number of sensors on site). Particularly, an accelerometer network well designed enables the condition evaluation of the structure and also the detection of eventual anomalies in its structural behaviour. This purpose is reached by an appropiate placement of several accelemeters on a structure. From that, it is possible to evaluate some dynamic parameters and vibrational levels under nstandard condition and, then, monitor the evolution of these parameters in real time. If it is detected an potential variation of a controlled parameter with respect to an initial state, it is feasible the presence of an anomaly or damage process over the structure, allowing further structural analysis and potentially the establishment of maintenance works.

This technique is adequate for being applied to bridges in general and, particularising, to some elements of them such as:

- Deck
- Arches
- Beams
- Piers
- Joints
- Abutments
- Tendons
- [..]

Some of them, like joints, are not so common and accelerometers can be representative of their behaviour only in few cases.

The key structural indicators evaluated whit MEMS accelerometers include:

- Frequencies, used for monitoring the whole structure status and, in some cases, characterise local components.
- Modal shapes, used to monitor the overall structure status.
- Vibrational levels to monitoring and maintenance activities for both the overall structure and/or specific elements of it (pier, abutment, joints).
- Damping ratio, used for the overall structure monitoring.

There are some main features that define the MEMS accelerometers:

- It is a low cost technology with a small size.
- Easy to transport and install (although the characteristics of infrastructures and the environment where the devices are installed may make the operation difficult).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- Applicable to different situations by only adjusting settings parameters.
- High sensitive to the environmental noise
- Acceleration can be measured in one or three axes.

2.5.9.2 Scenarios definition

MEMS accelerometers allow the carachterization of the dynamic behaviour of bridges and its monitoring in several operational conditions. However, it is necessary to choose correctly the layout and the technical specifications, such as sampling frequency, of the accelerometers. For that, bridge characateristics have to be taking into account, including for example, the statical scheme and the tehoretical modal parameters.

The elements of the structure, its material or the environmental conditions have no influence on the way of apply the technology, when their layout has been designed to locate sensors on strategical measurement points from a structural point of view, ant the post processing can identify local vs global responses, forcing actions frequencies vs structure own modal modes.

2.5.9.3 Technology characteristics

MEMS accelerometers are applicable to different elements and situations in order to obtain acceleration that leads to the assessment of some parameters which represent the structural behaviour. For this purpose, accelerometers allow the automatic acquisition of several measures at the same time. The measurements are mechanical and performed in static, as mean rotation, during the post processing phase.

The acquired information are numeric values to be stored in a file or a database, representing accelerations as a measure of gravity or in a Least Significant Bit way.

This information must be within the expected range of possible values. This range is determined by the application.

The system based on MEMS accelerometers has to include an ADC converter, a gateway, devices to repeat signals for long distances, cables for wired systems, SIM, antennas, battery for wireless system and an electric backbone.

2.5.9.4 Methodology: phases and tasks

It is important to design carefully the sensors layout by thinking about some aspects such as the following:

- The characteristics of the specific phenomenon to be monitored.
- Define Key Performance indicators
- Define sampling rate for each sensor
- Consider the key nodes or elements of the structure and add one sensor on each of them. For example, the number of the sensors and the position of each one.
- Consider environmental conditions.
- Consider redundancy of measuring points.
- If there are signal from different sensors to combine, sensors must be synchronized.

The phases to follow to perform in the right way the technology are:

1. Planning. It involves the planning and design of the system and the sensors calibration and testing.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2. Installation of the system.
3. Testing, including data acquistion storage and analysis.

2.5.9.5 Interfaces and Connections

The equipment components requiring connection will be wired. The transmission of the data collected by the accelerometer can be done by GSM networks, and will be stored in files in a suitable format or in a database. For this reason, it will be necessary to implement services that allow users/systems to add new data to the database and manage them (sort, delete or edit) to facilitate analysis.

The data transferred is numeric, so an appropriate protocol in this case is HTTP.

2.5.9.6 Resources

A breakdown of the human and material costs of each technology is given below. In the case of purchased equipment, their amortisation, the estimated performance for each task and a balance of the expected costs and benefits. Considering MEMS are usually implemented in a more sophisticated monitoring system, consisting in a wide number of sensors, next sections have been completed with the following assumptions, valid for accelerometer and clinometers:

The cost of human resources was estimated considering all the professional figures required to manage a bridge/tunnel monitoring system made of MEMS sensors (going from design to data analytics). The cost is always expressed in terms of 1 sensor (clinometer or accelerometer), even if in a real monitoring system the number of sensors is considerably higher. Besides, since a monitoring system is designed to be active for a long period of time, the considered time unit is equal to one year. The cost of material resources can be highly variable according to the desired sensors performances and to the technology chosen (e.g. wired or wireless systems). For this reason the cost is often given as a wide range of possible values. The duration of each task was estimated considering all the needed activities to manage a one-year monitoring system. Please notice that in this case the considered structural unit is bridge made of 5 spans.

2.5.9.6.1 Personnel

Human resource	**Cost (€)**	**Unit**
Software/Hardware engineer	72	Hour
Applied researched	37	Hour
Structural engineer	22	Hour
Data expert	19	Hour
Cloud developer	17	Hour
Coordinator	14	Hour
Project designer	8	Hour
Maintenance	9	Hour

Table 2.69 – Human resources for Accelerometers technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.9.6.2 Material resources

Material resource	Cost (€)	Unit
Accelerometer	850	Device
Cable (wired systems)	2	m
Gateway	2000	Device
Cloud	204,55	Day

Table 2.70 – Material resources for Accelerometers technique

The amortisation cost of each device and material is calculated on the basis of its purchase price:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Accelerometer	850	10,00%	3	70,00	3,64€
Cable (wired systems)	2	10,00%	3	70,00	0,01€
Gateway	2000	10,00%	3	70,00	8,57€

Table 2.71 – Amortisation of materials used in Accelerometers technique

2.5.9.6.3 Performance

Phase	Task	Duration (hours)	Unit
System planning	System planning and design	18	Bridge / year of monitoring
	Sensors calibration and planning	31	Bridge / year of monitoring
System installation	Quality control	8	Bridge / year of monitoring
Testing	Data acquisition	38	Bridge / year of monitoring
	Data storage	7	Bridge / year of monitoring
	Data analysis	67	Bridge / year of monitoring

Table 2.72 – Duration of tasks in Accelerometers technique

Task	Resource	Hours
System planning and design	Coordinator	12
	Project designer	3
	Structural engineer	3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Sensors calibration and planning	Software/Hardware engineer	31
Quality control	System manager	8
Data acquisition	Software/Hardware engineer	31
	Cloud developer	7
Data storage	Cloud developer	7
Data analysis	Applied researcher	32
	Structural engineer	19
	Data expert	17

Table 2.73 – Resources used in Accelerometers technique tasks

2.5.9.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Coordinator	hour	12	14,00 €	168,00€	13,00%	21,84 €	6,00%	10,08 €	199,92 €
Project designer	hour	3	8,00 €	24,00€	13,00%	3,12 €	6,00%	1,44 €	28,56 €
Structural engineer	hour	22	22,00 €	484,00€	13,00%	62,92 €	6,00%	29,04 €	575,96 €
Software/Hardware engineer	hour	62	72,00 €	4.464,00 €	13,00%	580,32 €	6,00%	267,84 €	5.312,16 €
Cloud developer	hour	14	17,00 €	238,00€	13,00%	30,94 €	6,00%	14,28 €	283,22 €
Applied researcher	hour	32	37,00 €	1.184,00 €	13,00%	153,92 €	6,00%	71,04 €	1.408,96 €
Data expert	hour	17	19,00 €	323,00€	13,00%	41,99 €	6,00%	19,38 €	384,37 €
Accelerometer	day	1	3,64 €	3,64€	13,00%	0,47 €	6,00%	0,22 €	4,33 €
Cable (wired systems)	day	1	0,01 €	0,01€	13,00%	0,00 €	6,00%	0,00 €	0,01 €
Gateway	day	1	8,57 €	8,57€	13,00%	1,11 €	6,00%	0,51 €	10,20 €
Cloud	day	1	204,55 €	204,55€	13,00%	26,59 €	6,00%	12,27 €	243,41 €
				7.101,77 €		923,23 €		426,11€	**8.451,11€**

Table 2.74 – Breakdown of costs and benefits for the budgeting of the Accelerometers technique

2.5.10 Micro Electro-Mechanical Systems (MEMS) - Clinometers

2.5.10.1 Purpose and main features

Micro electro-mechanical systems in general, and clinometers in particular (that could be biaxial accelerometers), allow both the evaluation of the condition of the structure and the detection of eventual anomalies which affects to its structural behaviour. With this objective in mind, several clinometers are placed in adequate places along the structure, enabling the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

observation of the displacements and deformations of a structure and deriving the anomalies and damage processes which are acting on it.

A network of clinometers allows the maintenance, monitoring and security for both bridges and tunnels. The detection of the different anomalies is not only applicable to the overall structure but it could also be applied in some specific structural elements of a structure such as:

- Deck
- Arches
- Beams
- Piers
- Joints
- Abutments
- Tendons
- [..]

Some of them, like joints, are not so common and accelerometers can be representative of their behaviour only in few cases.

Clinometers output is proportional to the sine of the angle between the sensing axis and the horizontal plane. Furthermore, there are some facts to be noted:

- MEMS clinometers are available, provided on board composed by an integrated circuit and some electronics elements
- Small rotations, close to 0 degrees, leads to maximum sensitivity and measurement accuracy due to the linearization of the calibration curve.
- Rotation angles near to 90 degrees entail sensitivity towards 0 withou the possibility of linearize it, so the measurement accuracy decreases with the increasing of the rotation angle.
- Only rotations around axis laying in the horizontal plane can be measured.
- There are available two types of clinometers depending its number of measuring axis: clinometers with single axes and clinometers with dual axis.
- Easy to transport and install (although the characteristics of infrastructures and the environment where the devices are installed may make the operation difficult).
- Low-cost technology.

The difference between the available types of clinometers are due to the setting values such as:

- Resolution
- Sensitivity or gain
- Range of acceleration values that can be measured
- Monoaxial or biaxial devices

2.5.10.2 Scenarios definition

MEMS clinometers are a useful tool to be added to a SHM system for measuring relative displacements, deformations and the loss of section in order to evaluate the static behaviour

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

of structures such as bridges and tunnels in a non-destructive way. Due to the fact that different types of clinometers with different chracteristics are available, their technical specifications as well as their layout must be chosen in accordance to the type of structure to be monitored.

Other circumstances such as materials or environment have no implications for the application of the technology.

2.5.10.3 Technology characteristics

The result to be obtained for a MEMS clinometer is the measure of the tilt along one or two axes depending of the type of clinometer. The technology allows to measure static or quasi static quantities, with a lower boundary close to 0 Hz.

The type of measurements obtained with MEMS clinometers are mechanical analog outputs with a power supplier with voltage range which tipically is between 0 and 5 volts, being possible to take several measures at the same time. So that, the information obtained is numeric and it is stored in a file or a database with the required format. Moreover, data must be in the expected range of values for the specific application.

The tools needed for this technology include an ADC converter, a gateway, devices to repeat signals for long distances, cables if it is used a wired system, SIM, antennas, battery if the system is wireless and an electric backbone.

The measurement accuracy is defined by the parameterisation of its settings parameters and it can also be affected by the errors due totemperature drifts. For this reason, it is advisable to add also an on-board temperature sensor to the final device.

2.5.10.4 Methodology: phases and tasks

It is important to design carefully the sensors layout by taking into account some aspects such as the following:

- The characteristics of the specific phenomenon to be monitored.
- Consider the key nodes or elements of the structure and add one sensor on each of them.
- Consider environmental conditions.
- Consider redundancy of measuring points.

The performance of the technique include the following tasks which have to be applied:

1. Planning. It consists on the system planning and design, the production of the sensors and, at last, the calibration and testing of the sensors.
2. Installation. It refers to the installation of the system and its functional control.
3. Testing. It involves the acquisition of the data, their storage and their post -processing and analysis.

2.5.10.5 Interfaces and Connections

The equipment components requiring connection will be wired. The transmission of the data collected by the accelerometer can be done by GSM networks, and will be stored in files in a suitable format or in a database. For this reason, it will be necessary to implement services that allow users/systems to add new data to the database and manage them (sort, delete or edit) to facilitate analysis.

The data transferred is numeric, so an appropriate protocol in this case is HTTP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.10.6 Resources

In including the following data, some assumptions have been made in order to simplify and display them in a simpler way. These assumptions are the same as for the accelerometers and can be found in section 2.5.9.6.

2.5.10.6.1 Personnel

Human resource	Cost (€)	Unit
Software/Hardware engineer	48	Hour
Applied researched	25	Hour
Structural engineer	15	Hour
Data expert	13	Hour
Cloud developer	12	Hour
Coordinator	9	Hour
Project designer	6	Hour
Maintenance	6	Hour

Table 2.75 – Human resources for Clinometers technique

2.5.10.6.2 Material resources

Material resource	Cost (€)	Unit
Clinometer	600	Device
Cable (wired systems)	2	m
Gateway	2000	Device
Cloud-based platform	204,55	Day

Table 2.76 – Material resources for Clinometers technique

The amortisation cost of each device and material is calculated on the basis of its purchase price:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
Clinometer	600€	10,00%	3	70,00	2,57€
Cable (wired systems)	2€	10,00%	3	70,00	0,01€
Gateway	2000€	10,00%	3	70,00	8,57€

Table 2.77 – Amortisation of materials used in Clinometers technique

2.5.10.6.3 Performance

Phase	Task	Duration (hours)	Unit

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

System planning	System planning and design	21	Bridge / year of monitoring
	Sensors calibration and planning	34	Bridge / year of monitoring
System installation	Quality control	9	Bridge / year of monitoring
Testing	Data acquisition	43	Bridge / year of monitoring
	Data storage	8	Bridge / year of monitoring
	Data analysis	75	Bridge / year of monitoring

Table 2.78 – Duration of tasks in Clinometers technology

Task	Resource	Hours
System planning and design	Coordinator	13
	Project designer	4
	Structural engineer	4
Sensors calibration and planning	Software/Hardware engineer	34
Quality control	System manager	9
Data acquisition	Software/Hardware engineer	34
	Cloud developer	8
Data storage	Cloud developer	8
Data analysis	Applied researcher	36
	Structural engineer	21
	Data expert	18

Table 2.79 – Reosurces used in Clinometers technology tasks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.10.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Coordinator	hour	13	14,00 €	182,00€	13,00%	23,66 €	6,00%	10,92 €	216,58 €
Project designer	hour	4	8,00 €	32,00€	13,00%	4,16 €	6,00%	1,92 €	38,08 €
Structural engineer	hour	25	22,00 €	550,00€	13,00%	71,50 €	6,00%	33,00 €	654,50 €
Software/Hardware engineer	hour	68	72,00 €	4.896,00 €	13,00%	636,48 €	6,00%	293,76 €	5.826,24 €
Cloud developer	hour	16	17,00 €	272,00€	13,00%	35,36 €	6,00%	16,32 €	323,68 €
Applied researcher	hour	36	37,00 €	1.332,00 €	13,00%	173,16 €	6,00%	79,92 €	1.585,08 €
Data expert	hour	18	19,00 €	342,00€	13,00%	44,46 €	6,00%	20,52 €	406,98 €
Accelerometer	day	1	2,57 €	2,57€	13,00%	0,33 €	6,00%	0,15 €	3,06 €
Cable (wired systems)	day	1	0,01 €	0,01€	13,00%	0,00 €	6,00%	0,00 €	0,01 €
Gateway	day	1	8,57 €	8,57€	13,00%	1,11 €	6,00%	0,51 €	10,20 €
Cloud	day	1	204,55 €	204,55€	13,00%	26,59 €	6,00%	12,27 €	243,41 €
				7.821,70 €		1.016,82€		469,30€	**9.307,82€**

Table 2.80 – Breakdown of costs and benefits for the budgeting of Clinometers technology

2.5.11 Optical and Visual Testing: Boroscopy and endoscopy

2.5.11.1 Purpose and main features

Optical and visual testing, like boroscopy and endoscopy, are applicable to evaluate the status of different structural elements of bridges and tunnels. This evaluation includes the inspection of the elements in order to assess different aspects that affects to the maintenance of the infrastructures and which are applicable to the whole structure.

No physical quantity is directly measured with endoscopy and boroscopy, but the parameters are taken for visual assessment.

With independance of the selection of boroscopy or endoscopy for the visual assessment, the aspect to evaluate are the same:

- Holes
- Deformation
- Obstruction
- Rupture
- Cracks

It should be noted that rupture happens when bursting force exceeds the strength of the closed material and cause the break or burst suddenly, so that the material fail instantaneously. Cracks (fractures) propagates slowly in the material and fails it over a period of time.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

There are different types of boroscopes and endoscopes, but all leads to the obtention of the same kind of information. The technology of the boroscopes includes:

- Rigid/half rigid borescopes for diameter ranges of 4 to 19.
- Flexible borescopes with diameter ranges within 9.5 to 44 mm.
- Micro borescopes with diameters within the range of 1 to 3.5 mm.
- Periscopes for using in underwater or high/low pressure conditions.

Within the available endoscopes, there are two types:

- Rigid endoscopes.
- Flexible endoscopes.

Despite, both boroscopy and endoscopy are usually considered as non-destructive testing technologies, in particular situations they can be considered into destructive technologies for the need of inducing minor damages. This particular situation occurs when it is difficult to reach some area.

Some good characteristics of this technique is that images can be directly recorded on a memory card, the small diameter of the camera that allows to pass through tinies holes and the durability of the device due to its stainless steel construction. Another important feature is that the variety of available resolution allow to balance the quality-price ratio. Nevertheless, the operator experience can influence the results, feature which is being less determinant due to the technology advances.

2.5.11.2 Scenarios definition

The application of optical and visual testing technologies leads to the detection and photograph of anomaly conditions of sections in the structural elements of bridges and tunnels with cracks and deformations (visible damage effects) and allow also to the detection of areas affected by corrosion and chemical attacks, when visible on the surface.

Regardless if it is used boroscopy or endoscopy, it does not involves changes in the application scenario due to factors such as environment type, element of the structure or type of structure or materials to study.

2.5.11.3 Technology characteristics

These techniques are based on the acquisition of optical images and videos from which analyze the status of the structures. It is possible to obtain results from this technique manually and in a digital format and perform that in a static way, being acquired one result at each time.

The obtained information are images or videos which could be shown in a screen. Moreover, these graphic data can be stored in a file with the required data format (explained in *3, Preprocessing*) for further analysis. Regarding the accuracy of the system,it depends on the characteristics of the camera, specially the resolution, and it also depends on the experience of the operator.

The necessary tools to use for the application of these techniques are the following:

- Camera supplied with colour display. This camera has to be of the desired type of optical testing (borescope and endoscope).
- Batteries
- Micro SD card
- Computer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Relative to the assessment based on the visual inspection,useful notes and general principles to take into account can be found in the standard EN 13018:2016.

2.5.11.4 Metodology: phases and tasks

The main aspect to take into account about the optical and visual testing, both in boroscopy and endoscopy techniques, is that the performance of the survey implies that the operator has to be able to access to the tested areas. However, this circunstance is not always possible.

The realization of the boroscopy or endoscopy involves the following tasks:

1. Planning. It includes:
   - Reading previous inspection reports
   - Decision regarding the elements to be investigated in the first place
   - Needed resources to reach difficult areas under bridge/tunnel.
2. On-site investigation: to help in the decision making and to prepare the resources on-site for the inspection of the damaged areas.
3. Reporting. It involves:
   - Identification of: the equipment, inspected area, elements within this area, research scope and survey date.
   - Labelling of graphic data with date, time, description of the inspection site and surrounding conditions.

2.5.11.5 Interfaces and Connections

The data from the borescopes are saved in a micro SD Card, so there are no physical connection established between the computer and the borescope. At the moment of transferring the data, it is done by a service which collect from the micro SD card, when it is connected on the computer, and send them to the storage, for example allocated in a web cloud. This sending has to be done using an adequeate protocol such as FTP.

It has to be implemented also an user interface to allow the data management and visualization by the users. For this purpose, services to extract data from the storage and make accessible to the further application/analyses have to be implemented.

2.5.11.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.11.6.1 Personnel

Human resource	Cost (€)	Unit
Construction appraisar	25	Hour
Bridge inspector	20	Hour
Engineer	15	Hour
Assistant with higher education	13	Hour

Table 2.81 – Human resources for Boroscopy and endoscopy techniques

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.11.6.2 Material resources

Material resource	Cost (€)	Unit
Portable borescope with 8GB micro SD card	700	Device
ortable endoscope 40 m fi 23mm	834,59	Device
Batteries AA	8,39	Set
Standard computer	602	Device
micro SD card 128 GB	17	Piece

Table 2.82 – Material resources for Boroscopy and endoscopy techniques

The amortisation cost per day of the materials used is as follows:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
Portle borescope with 8GB micro SD card		700,00€	10,00%	1	50,00	12,60€
Portable endoscope 40 ml fl 23mm		834,59€	10,00%	1	50,00	15,02€
Batteries AA		8,39€	10,00%	1	1,00	7,55€
Computer	Standard	602,00€	10,00%	3	50,00	3,61€
micro SD card 128 GB		17,00€	10,00%	1	50,00	0,31€

Table 2.83 – Amortisation of materials used in Boroscopy and endoscopy techniques

2.5.11.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	-	1-5	depends on the size
On-site investigation	-	1-10	depends on the size
Photo and video footage	-	1-10	depends on the size
Display of the collected material and analysis	-	1	depends on the size
Reporting	-	2-5	depends on the size

Table 2.84 – Duration of tasks in in Boroscopy and endoscopy techniques

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Task	Resource	Hours
Planning	Bridge Inspector, Construction appraisar	1-5
On-site investigation	Bridge Inspector	1-10
Photo and video footage	Engineer, Bridge Inspector	1-10
Display of the collected material and analysis	Operator, computer	1
Reporting	Bridge Inspector, Construction appraisar	2-5

Table 2.85 – Resources used in Boroscopy and endoscopy techniques tasks

2.5.11.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Portle borescope with 8GB micro SD card	Day	1,00	12,60€	12,60€	13,00%	1,64 €	6,00%	0,76 €	14,99 €
Portable endoscope 40 ml fl 23mm	Day	1,00	15,02€	15,02€	13,00%	1,95 €	6,00%	0,90 €	17,88 €
Batteries AA	Day	1,00	7,55€	7,55€	13,00%	0,98 €	6,00%	0,45 €	8,99 €
Computer	Day	1,00	3,61€	3,61€	13,00%	0,47 €	6,00%	0,22 €	4,30 €
micro SD card 128 GB	Day	1,00	0,31€	0,31€	13,00%	0,04 €	6,00%	0,02 €	0,36 €
Construction appraisar	Hour	10,00	25,00€	250,00€	13,00%	32,50 €	6,00%	15,00 €	297,50 €
Bridge inspector	Hour	30,00	20,00€	600,00€	13,00%	78,00 €	6,00%	36,00 €	714,00 €
Engineer	Hour	10,00	15,00€	150,00€	13,00%	19,50 €	6,00%	9,00 €	178,50 €
Assistant with higher education	Hour	1,00	13,00€	13,00€	13,00%	1,69 €	6,00%	0,78 €	15,47 €
				1.013,31 €		131,73 €		60,80 €	**1.251,99 €**

Table 2.86 – Breakdown of costs and benefits for the budgeting of Boroscopy and endoscopy techniques

2.5.12 Qualitative Chemical Methods

2.5.12.1 Purpose and main features

There are chemichal methods used for the qualitative assessment of some elements of the infrastructures. These methods are based on the determination of pH of the material, that can be concrete, technical ceramic, building lime, slag, cement, gravel, pigments or ferroalloys to

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

determine changes in its values under the effect of environmental conditions. The changes are due to the physicochemichal change due to the constant influence of the carbon dioxide from the air as well as the indoor atmosphere of building structures.

Both bridges and tunnels are structures where qualitative chemichal methods can be applied for maintenance works. Further specifying, the parts susceptible of being evaluated with this technique include:

- Bridge decks.
- Concrete piers and docks.
- Substructure.
- Tunnel lining.
- Foundations.

Several sensors and methods may be used for its application such as:

- pH indicators.
- Uranyl-acetate treatment.
- Half-cell potentials method.
- Electrical resistivity tomography.
- InfraRed Spectroscopy.

Applying the sensors and methods mentioned above on structural elements, there are some damage effects that can be detected:

- Loss of section.
- Cracks.
- Obstruction.
- Displacement.
- Debonding.
- Delamination.
- Spalling.
- Reinforcement bar corrosion.

Some parameters are quantificable such as:

- pH.
- Range number.
- Size for the bar cover.
- Change of cover depth.
- Carbonation process.
- Alkali-aggregate reaction.

2.5.12.2 Scenarios definition

The difference in the application of the this technique will be derived from the different characteristics of the specific method to apply. However, the application does not depend on

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

the element of the structure to be analyzed, neither its material or the characteristics of the environment in which it is located.

The method to use determines the equipment used, changing due to that the scenario.

2.5.12.3 Technology characteristics

The qualitative chemical methods are designed for evaluating physicochemical changes by the usage of different equipment and calculating the desired parameters from the measurements obtained. Manual or even automatic measurements are possible. These measurements will be digital and performed in a static way.

It depends on the application over the time, being possible to take only one measure or several measures in a specific period of time.

Some different tools can be used in accordance to the test to perform, including:

- pH fenoloftalein reagent 1%.
- Uranylacetat reagent.
- pH Thymolphtalein reagent.
- IR spectrometer and software.
- Electrical resistivity tomograph.

The results will be shown in a screen and could be stored in a file.

The procedure to follow the performance of the test is guided by some standards as the ASTM F710-11 (for methods based on pH measurement), EN 14630:2006 (for the test methods based on the carbonation determination depth) and EN 1239-12:2020 (for the determination of the carbonation resistance of concrete).

2.5.12.4 Metodology: phases and tasks

One important requirement to be taken into account before the realization of the test is that the surface of the concrete should be cleaned and smoothed.

The phases of the technique differ depending on the chosen method, but a general workflow for the technique could be:

1. Planning. It is based on the decision making about the element to study and its characteristics, including the selection of the particular method to use.
2. Preparation: cleaning and smoothing the surface.
3. Calibration of the equipment.
4. Data acquisition.
5. Data analysis.
6. Validation.

2.5.12.5 Interfaces and Connections

The collection of the data could be done manually by the operator or automatically by some tools as the IR spectrum. The connection with the IR spectrum can be done using RS-232 or bluetooth.

It is needed an user interface which implements services for managing the data allowing the data modification and visualization.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.12.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.12.6.1 Personnel

Human resource	Cost (€)	Unit
Laboratory Technician	19,34	Hour
Laboratory Specialist	21,94	Hour

Table 2.87 – Human resources for Qualitative Chemical Methods

2.5.12.6.2 Material resources

Material resource	Cost (€)	Unit
pH fenoloftalein reagent 1%	13,51	100 ml
Uranylacetat reagent	389,30	25 g
pH Thymolphthalein reagent	26,68	10 g
Half-cell potential testing equipment	1532,60	Device
Infrared Spectroscopy analysis of concrete in external laboratory	129,00	1 order
IR spectrometer + software	45217,50	Device
Electrical resistivity tomograph + software	36173,10	Device

Table 2.88 – Material resources for Qualitative Chemical Methods

The amortisation cost per day of the materials used is as follows:

Product	Price	% residual	Year	Uses/Year	Amortisation/day
pH fenoloftalein 1%	13,51€	10,00%	1	1,00	12,16€
Uranylacetat reagent	389,30€	10,00%	1	1,00	350,37€
pH Thymoplhthalein reagent	26,68€	10,00%	1	1,00	24,01€
Half-cell potential test equipment	1.532,60€	10,00%	1	50,00	27,59€
Infrared Spectroscopy analysis of concrete (external laboratory)	129,00€	10,00%	1	1,00	116,10€
IR spectrometer + software	45.217,50€	10,00%	3	50,00	271,31€
Electrical resistivity tomograph + software	36.173,10€	10,00%	3	50,00	217,04€

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table 2.89 – Amortisation of materials used in Qualitative Chemical Methods

2.5.12.6.3 Performance

Phase	Task	Duration (hours)	Unit
Infrared Spectroscopy	Switching on the spectrometer	1-2 minutes	Sample
	Controlling the instrument	15 minutes	Sample
	Atmospheric suppression	5 minutes	Sample
	Scan and Instrument Setup	10 minutes	Sample
	Scan collection	5 minutes	Sample
	Quality checks	5-30 minutes	Sample
Routine maintenance	Cleaning the spectrometer	15 minutes	-
	Cleaning the display	5 minutes	-
Data analysis	IR Spectrum analysis	1-2 minutes	Sample (depends on the complexity)
	Reporting	15 minutes	Sample

Table 2.90 – Duration of tasks in Qualitative Chemical Methods

Task	Resource	Hours
Switching on the spectrometer	Laboratory Technician, IR Spectrometer	1-2 minutes
Controlling the instrument	Laboratory Technician, IR Spectrometer	15 minutes
Atmospheric suppression	Laboratory Technician, IR Spectrometer	5 minutes
Scan and Instrument Setup	Laboratory Technician, IR Spectrometer	10 minutes
Scan collection	Laboratory Technician, IR Spectrometer	5 minutes
Quality checks	Laboratory Technician, IR Spectrometer	5-30 minutes
Cleaning the spectrometer	Laboratory Technician, IR Spectrometer	15 minutes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Cleaning the display	Laboratory Technician, IR Spectrometer	5 minutes
IR Spectrum analysis	Laboratory Technician, IR Spectrometer	1-2 minutes
Reporting	Laboratory Technician, IR Spectrometer	15 minutes

Table 2.91 – Resources used in Qualitative Chemical Methods tasks

2.5.12.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
pH fenoloftalein 1%	Day	1,00	12,16€	12,16€	13,00%	1,58 €	6,00%	0,73 €	14,47 €
Uranylacetat reagent	Day	1,00	350,37€	350,37€	13,00%	45,55 €	6,00%	21,02 €	416,94 €
pH Thymoplhthalein reagent	Day	1,00	24,01€	24,01€	13,00%	3,12 €	6,00%	1,44 €	28,57 €
Half-cell potential test equipment	Day	1,00	27,59€	27,59€	13,00%	3,59 €	6,00%	1,66 €	32,83 €
Infrared Spectroscopy analysis of concrete (ext. Lab.)	Day		116,10€	0,00€	13,00%	- €	6,00%	- €	- €
IR spectrometer + software	Day	1,00	271,31€	271,31€	13,00%	35,27 €	6,00%	16,28 €	322,85 €
Electrical resistivity tomograph + software	Day		217,04€	0,00€	13,00%	- €	6,00%	- €	- €
Laboratory Technician	Day	1,00	19,34€	19,34€	13,00%	2,51 €	6,00%	1,16 €	23,01 €
Laboratory Specialist	Hour	3,00	21,94€	65,82€	13,00%	8,56 €	6,00%	3,95 €	78,33 €
				356,47€		46,34 €		21,39 €	**917,01 €**

Table 2.92 – Breakdown of costs and benefits for the budgeting of Qualitative Chemical Methods

2.5.13 Quantitative Chemical Methods

2.5.13.1 Purpose and main features

Infrastuctures are exposed to many environmental factors that can cause material degradation affecting to the durability of the structures. Taking in mind these issues, there are chemical methods which are developed for the quantitatively assessment of the rate of degradation processess in structural parts of infrastructures such as bridges and tunnels. For the original concrete, firts, its basic chemical characteristics are examinated, including aspects like pH and the content of chloride and sulfate ions. Then, more sophisticated methods for

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

quantitative assessment are used to evaluate the content of them. The tests can be repeated in specific period of time to see how the values change.

The obtained results are evaluated in order to take decisions relative to the structures maintenance which may:

- Be repaired without any additional treatment.
- Undergo further treatment in case the results point to possible corrosion and the condition of the concrete can still be improved.
- Not be qualified for repair due to a significant threat to durability.

Quantitative chemical methods are applicable to specific elements in both bridges and tunnels structures, such as:

- Reinforced concrete slabs of the load-bearing bridge structure.
- Bridge abutments.
- Cable-concrete girders.
- Slabs.
- Concrete beams.

Through the usage of this technique is possible to evaluate quantitatively the following parameters of the structures:

- Measurement of corrosion rate, in terms of thickness of steel being dissolved per year, in μm/year.
- Chloride content in μg/l.

There are also detectable, as consequence,the following aspects:

- Loss of section.
- Cracks.
- Obstruction/impeding.
- Displacement.
- Debonding.
- Spalling.

There are several methods for the observation of the different parameters:

- Galvanostatic Pulse technique for the obtention of the corrosion rate.
- Gravimetric method to obtain the content in sulfate ions.
- Argentometric titration for obtaining the content in chloride.
- Ion Chromatography for the soluble anions and cations content.
- Chloride Diffusion test for the concentration of the chloride ions.

2.5.13.2 Scenarios definition

The application of the technique differs depending on the material, since the characteristics of each sample will be different. Considering this issue, it is important to specify the materials which could be useful and lead to the different application scenarios:

- Concrete.
- Reinforced concrete.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- Polymer.
- Composites.
- Biomolecules.
- Nanomaterials.

Other aspects as the environment and the structure features as the type or the particular element, will not influence the way of performing the technique because the tests are performed in a laboratory.

2.5.13.3 Technology characteristics

With the quantitatively chemical methods, depending on the used method, can be performed digital and static measurements in both ways, manual and automatic. In terms of time, the measures can be acquired in two ways: one measure at each time or several measurements at the same time.

The equipment to use is different for each method such as:

- Potentionmetric and argentometric titrator.
- Ion chromatograph.
- Scale.
- Chloride diffusion test equipment.

Depending on the equipment required, the information created in this technique will be numeric, graphic or plotteed in the IR spectrum. This collected data will be structured in a file, shown on a screeen or been stored in a storage medium.

In the same way, the validation of the results will be different in each case. For the potentiometric titration, their results should be validated with another instrumental technique such as ion chromatography, while in the chloride diffusion test and the ions migration in electrical field, there are used linear, Freudlich and Langmuir isotherms to fit the relationship between acquired data and experimental data.

The workflow and characteristics to be cosidered while the performance of the test are defined in the standard ISO 572594.

2.5.13.4 Metodology: phases and tasks

Within the aspect to consider for the test performance in order to have a methodology which leads to good results, there are some aspects to think about:

- The test samples must be extracted from representative places in the structure , as for example, the cover of the cocrete at the reinforcement surface.
- Take samples from different depths.

The tasks will be different for each method, but in a general the phases of the test could be something similar to:

1. Planning. It is based on the decision making about the element to study and its characteristics, including the selection of the particular method to use.
2. Preparation: cleaning and smoothing the surface.
3. Calibration and preparation of the equipment. It has to be done according to the standard and the manufacturer manual.
4. Data acquisition.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

5. Data analysis.
6. Validation.

Acquisition of the results. It will be different for each method.

Reporting of the results and their validation. The main difference between the different methods will be in the intermediate stages.

2.5.13.5 Interfaces and Connections

The collection of the data could be done manually by the operator or automatically by some tools as the IR spectrum. So, it is needed an user interface which implements services for managing the data allowing the data modification and visualization.

In the case of the chromatograph, it has to be connected by a protocol such as RS-232 or Ethernet for the automated data acquisition.

2.5.13.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.13.6.1 Personnel

Human resource	Cost (€)	Unit
Laboratory Technician	19,34	Hour
Laboratory Specialist	21,94	Hour

Table 2.93 – Human resources for Quantitative Chemical Methods

2.5.13.6.2 Material resources

Material resource	Cost (€)	Unit
Automatic potentiometric titrator	7841,30	Device
Potentiometric titration in external laboratory	6,80	Sample
Argentometric titrator	5887,32	Device
Ion Chromatograph + software	7234,80-13565,25	Device
Concrete Chloride Diffusion Tester for Durability Test	2260,88-3165,22	Device

Table 2.94 – Material resources for Quantitative Chemical Methods

The amortisation cost per day of the materials used is as follows:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
Automatic Potentiometric Titrator		7.841,30€	10,00%	2	50,00	70,57€

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Potentiometric titration in external laboratory		6,80€	10,00%	1	1,00	6,12€
Argentometric titrator		5.887,32€	10,00%	2	50,00	52,99€
Ion Chromatograph + software		13.565,25€	10,00%	2	50,00	122,09€
Concrete chloride Diffusion Tester	For durability	3.165,22€	10,00%	2	50,00	28,49€

Table 2.95 – Amortisation of materials used in Quantitative Chemical Methods

2.5.13.6.3 Performance

Phase	Task	Duration (hours)	Unit
Ion Chromatography-preparation stage	Power up the system	1 minute	Sample
	Set up the reservoir	5 minute	Sample
	Check the connections	10-20 minutes	Sample
	Prime the pump	1 minute	Sample
	Set operating conditions	2 minutes	Sample
	Equilibriate the system	10-30 minutes	Sample
Preparation of the samples	Pretreating, diluting	1-2 h	Sample
	Verify operating status	2 minutes	Sample
	Process samples	1-2 h	Sample
Ion chromatography-sample processing	Load the samples	few seconds	Sample
	Start of data acquisition	few seconds	Sample
	Autozero	few seconds	Sample
	Stop data acquisition	few seconds	Sample
	Save the manual sequence data	few seconds	Sample

Table 2.96 – Duration of tasks in Quantitative Chemical Methods

Task	Resource	Hours
Power up the system	Laboratory Technician, chromatograph	1 minute

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Set up the reservoir	Laboratory Technician, chromatograph	5 minute
Check the connections	Laboratory Technician, chromatograph	10-20 minutes
Prime the pump	Laboratory Technician, chromatograph	1 minute
Set operating conditions	Laboratory Technician, chromatograph	2 minutes
Equilibriate the system	Laboratory Technician, chromatograph	10-30 minutes
Pretreating, diluting of the samples	Laboratory Specialist	1-2 h
Verify operating status	Laboratory Specialist	2 minutes
Process samples	Laboratory Specialist	1-2 h
Load the samples	Laboratory Specialist	Few seconds
Start of data acquisition	Laboratory Specialist, chromatograph	Few seconds
Autozero	Chromatograph	Few seconds
Save the manual sequence data	Laboratory Specialist	Few seconds
Analysis of the data	Laboratory Specialist	1-2 h

Table 2.97 – Resources used in Quantitative Chemical Methods tasks

2.5.13.6.4 Cost/benefit analysis

Resource	**Unit**	**Units**	**Cost/Unit**	**Cost**	**%O**	**O**	**% B**	**B**	**Budget**
Automatic Potentiometric Titrator	Day		70,57€	0,00€	13,00%	- €	6,00%	- €	- €
Potentiometric titration in external laboratory	Day		6,12€	0,00€	13,00%	- €	6,00%	- €	- €
Argentometric titrator	Day		52,99€	0,00€	13,00%	- €	6,00%	- €	- €
Ion Chromatograph + software	Day	1,00	122,09€	122,09€	13,00%	15,87 €	6,00%	7,33 €	145,28 €
Concrete chloride Diffusion Tester	Day		28,49€	0,00€	13,00%	- €	6,00%	- €	- €
Laboratory Technician	Day	1,00	19,34€	19,34€	13,00%	2,51 €	6,00%	1,16 €	23,01 €
Laboratory Specialist	Hour	6,00	21,94€	131,64€	13,00%	17,11 €	6,00%	7,90 €	156,65 €
				150,98€		19,63 €		9,06 €	**324,95 €**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Table 2.98 – Breakdown of costs and benefits for the budgeting of Quantitative Chemical Methods

2.5.14 Radiological and Nuclear Methods

2.5.14.1 Purpose and main features

Radiological methods are used to determine defects that are not visible to the naked eye in various types of structures. They will therefore be used to carry out maintenance work on both tunnels and bridges.

It will also be possible to apply these methods to specific structural elements such as pillars, rivets, bolts, welded joints, retaining walls, culverts or foundations.

Within this technique, the following methods can be distinguished:

- X-ray computed tomography/Gamma
- Neutron radiography
- Nuclear Magnetic Resonance Spectroscopy

Through its application it will be possible to determine the following parameters and damage to the elements of the structure:

- Crack dimensions
- Microcracking progress
- Detection of free chloride molecules and quantification
- Concrete durability (quantified by certain characteristics such as porosity, sorptivity and permeability)
- Debonding
- Delamination
- Displacement
- Loss of section

2.5.14.2 Scenarios definition

When applying these methods, there are no differences depending on which element is to be studied, which infrastructure it belongs to or in which environment it is located.

It is necessary to take into account what material it is made of. This is because most of the parameters set in the software for each test will be adjusted according to the material and sample preparation.

2.5.14.3 Technology characteristics

Radiological and nuclear methods allow digital measurements to be obtained automatically and manually. It is possible to take a single measurement, several measurements at the same time or several measurements over a specific period of time.

The type of information will be both numerical and graphical, stored in files that can be consulted on a screen and stored on physical storage media and in databases.

The equipment necessary to apply this technique consists of :

- Computed tomograph

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- Nuclear Magnetic Resonance Spectrometer
- Isotopic sources
- Neutron Radiograph (reactors, accelerators)
- Computer
- Software for the NMR and processing of the images from CT
- Neutron Radiography

2.5.14.4 Methodology: phases and tasks

There is a barrier to the usefulness of this type of method due to the presence of ionising radiation, which requires strict standards to be applied during operation. This, in most cases, limits radiological methods to laboratory inspections.

In order to apply them to obtain data and results, it is necessary to distinguish the following phases and tasks:

1. Preparation. It envolves:
    - Situational sketch of the studied bridge
    - Decision regarding the sample collection for specific parts of the construction
2. Sample collection:
    - Sample collection from the parts under studies
3. Calibration (laboratory):
    - Setting the parameters for test configuration
4. Sample preparation (laboratory)
    - Treatment of the samples for specific test configuration
5. Measurement. It includes:
    - NMR test
    - Computed tomography scan
    - Neutron radiography scan
6. Data analysis
7. Reporting

2.5.14.5 Interfaces and Connections

This technique involves the implementation of services to visualize and manage the data received from it and also to collect them from the source which will be a spectrometer.

The data is collected from the spectrometer, which is connected to a computer via a serial port or bluetooth.

2.5.14.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.14.6.1 Personnel

Human resource	Cost	Unit
Bridge Inspector	23,21	Hour

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Laboratory Specialist	21,94	Hour

Table 2.99 – Human resources for Radiological and Nuclear Methods

2.5.14.6.2 Material resources

Material resource	Cost	Unit
Neutron Radiography (reactors, accelerators)	88 867	Device
Nuclear Magnetic Resonance Spectrometer 60 MHz NMR	32 041,45	Device
Isotopic sources	91 547	-
Nuclear Magnetic Resonance Spectrometer 90 MHz NMR	119011,10	Device
Benchtop/ tabletop NMR	36618,80 - 119011,10	Device
Computed tomograph	90 505,55 - 2 288 675	Device

Table 2.100 – Material resources for Radiological and Nuclear Methods

The amortisation cost per day of the materials used is as follows:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
Neutron Radiography		88.867,00€	10,00%	5	50,00	319,92€
Nuclear Magnetic Resonance Spectometer	60 Hz	32.041,45€	10,00%	5	50,00	115,35€
Isotopic sources		91.547,00€	10,00%	5	50,00	329,57€
Nuclear Magnetic Resonance Spectometer	90 Hz	119.011,10€	10,00%	5	50,00	428,44€
Benchtop/tabletop NMR		119.011,10€	10,00%	5	50,00	428,44€
Computed tomograph		2.288.675,00€	10,00%	5	100,00	4.119,62€

Table 2.101 – Amortisation of materials used in Radiological and Nuclear Methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.14.6.3 Performance

Phase	Task	Duration (hours)	Unit
Preparation	Situational sketch of the studied bridge	1	Bridge
	Decision regarding the sample collection for specific parts of the construction	1	Bridge
Sample collection	Sample collection from the parts under studies	1-8	Bridge
Calibration (laboratory)	Setting the parameters for test configuration	1-3	-
Sample preparation (laboratory)	Treatment of the samples for specific test configuration	1-3	-
Measurement	NMR test	1	Sample
	Computed tomography scan	1,,5	Sample
	Neutron radiography scan	0,5	Sample
Data analysis	Interpretation of the NMR spectra	0,1-3	Sample
	Interpretation of the CT scan	0,5-1	Sample
	Interpretation of the Neutron radiograph	1	Sample
Reporting	Analysis of the series of tests for the structure	1-5	Sample

Table 2.102 – Duration of tasks in Radiological and Nuclear Methods

Task	Resource	Hours
Situational sketch of the studied bridge	Bridge Inspector	1
Decision regarding the sample collection for specific parts of the construction	Bridge Inspector	1
Sample collection from the parts under studies	Laboratory Specialist	1-8

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Setting the parameters for test configuration	Laboratory Specialist	1-3
Treatment of the samples for specific test configuration	Laboratory Specialist	1-3
NMR test	Laboratory Specialist, NMR spectrometer	1
Computed tomography scan	Laboratory Specialist, Computed tomograph	1,,5
Neutron radiography scan	Laboratory Specialist, Neutron radiograph	0,5
Interpretation of the NMR spectra	Laboratory Specialist	0,1-3
Interpretation of the CT scan	Laboratory Specialist	0,5-1
Interpretation of the Neutron radiograph	Laboratory Specialist	1
Analysis of the series of tests for the structure	Bridge Inspector	1-5

Table 2.103 – Resources used in Radiological and Nuclear Methods tasks

2.5.14.6.4 Cost/Benefit Analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Neutron Radiography	Day	1,00	319,92€	319,92€	13,00%	41,59 €	6,00%	19,20 €	380,71 €
Nuclear Magnetic Resonance Spectometer 60Hz	Day		115,35€	0,00€	13,00%	- €	6,00%	- €	- €
Isotopic sources	-	1,00	329,57€	329,57€	13,00%	42,84 €	6,00%	19,77 €	392,19 €
Nuclear Magnetic Resonance Spectometer 90 Hz	Day	1,00	428,44€	428,44€	13,00%	55,70 €	6,00%	25,71 €	509,84 €
Benchtop/tabletop NMR	Day		428,44€	0,00€	13,00%	- €	6,00%	- €	- €
Computed tomograph	Day	1,00	4.119,62 €	4.119,62 €	13,00%	535,55 €	6,00%	247,18 €	4.902,34 €
Bridge Inspector	Hour	7,00	23,21€	162,47€	13,00%	21,12 €	6,00%	9,75 €	193,34 €
Laboratory Specialist	Hour	19,40	21,94€	425,64€	13,00%	55,33 €	6,00%	25,54 €	506,51 €
				4.707,72 €		612,00 €		282,46 €	**6.884,93 €**

Table 2.104 – Breakdown of costs and benefits for the budgeting of Radiological and Nuclear Methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.15 Remote sensing

2.5.15.1 Purpose and main features

Satellite remote sensing allows, in a non-invasive way, collecting information through the observation and mapping of the earth surface. Thus, it is possible to acquire, among others, satellite images about the object to be measured without having physical contact with it.

Satellites are usually used for monitoring of different types of infrastructures because of the advantages they offer, like the wide geographical and temporal coverage achieved in a single analysis or the available historical data through old images. However, a number of factors have to be taken into account, such as the resolution of the images and the need for a large storage capacity for them, or weather conditions, which may be unfavourable for data capture or image interpretation.

According to the signal source or sensor used to explore the object, two kinds of data capture can be distinguished:

- Actives: radar satellite images
- Passives: optical satellite images

Active and passive satellites are determined by the resolution at which the sensor is capable of reaching. In this sense, it is more common to use high-resolution images of active sensors for infrastructure monitoring.

Through monitoring, it will be possible to identify the following structural damage:

- Ruptures
- Holes
- Obstruction/impending
- Cracks
- Scaling
- Crushings
- Debonding
- Deformations
- Displacements

Due to the resolution of the images, all units are expressed as a minimum in cm and in True, False values. Deformations and displacements can be quantified in mm/year.

2.5.15.2 Scenarios definition

As previously mentioned, the use of satellites to capture optical data only allows to capture data on the surface of the earth, so this makes it unfeasible to use images for tunnels. In this case, bridges will be the main structures in which this technique will be employed.

Capturing images of the earth's surface does not concern any particularity depending on the type of infrastructure. The data acquisition by satellite remote sensing allows the study of the entire structure itself, as a whole, without depending on what type of structural element it is constituted by. This is because with satellite images, it is not possible to take elements in detail. Despite the fact that there may be small errors, the images are not affected in their measurement by the material of the structure or the environment type in which it is located.

It should be noted that it is necessary to analyse in advance what is the objective of the study to be carried out with the use of one type of satellite or another, depending on what it wants to measure. Start from this first decision, it must be considered that the meteorological

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

conditions affect the data capture too. It is therefore necessary to review or filter the choice of the day of the image that is intended to be used. In addition, it is important to know the different data sources from where images can be downloaded for use, whether public or private.

2.5.15.3 Technology characteristics

There are many ways to capture the data, so the most used sensors for infrastructure monitoring will be considered here, that is active sensors to capture images:

1. SAR-mode “Stripmap”

   The conventional SAR strip mapping mode assumes a fixed pointing direction of the radar antenna broadside to the platform track. A strip map is an image formed in width by the swath of the SAR and follows the length contour of the flight line of the platform itself. A detailed description of this mode you'll find on the topic SLAR.

2. SAR-mode “Spotlight”

   Spotlight-SAR is a mode of SAR operation for obtaining high-resolution by steering the radar beam to keep the target within the beam for a longer time and thus form a longer synthetic aperture. Spotlight SAR is capable of extending the high-resolution SAR imaging capability significantly. As more pulses are used, the azimuth resolution increases. This is achieved by keeping a target within the spotlight illumination of the radar beam for a longer time through electronic beam steering, resulting in a longer synthetic aperture. Spotlight SAR mode of operation is usually at the expense of spatial coverage, as other areas within a given accessibility swath of the SAR cannot be illuminated while the radar beam is spotlighting over a particular target area.

3. SAR-mode “Scan”

   A synthetic aperture radar having the capability to illuminate several subswaths by scanning its antenna off-nadir into different positions. This is the SAR-mode “Scan”.

With this type of sensor it will be possible to take digital measurements, either through a point image to study the current status of the structure or several images for periodical measurements to monitor the evolution of a structure over time.

Once the imagery has been obtained, which can be from free commercial satellites, equipment is needed to exploit the data. This usually consists of a high-performance computer, recording software, storage hardware and processing software.

The captured data are stored in a COSAR format file. The file should be checked for corruption and the information it contains should be validated. Further information on these aspects is given in Chapter 3.

2.5.15.4 Methodology: phases and tasks

Some relevant aspects to have into account for the application of the technology are the next ones:

- Study of the environment in which the object / infrastructure is placed.
- Choice of the type of satellite image appropriate for the case study.
- Study of the number of images required for analysis.
- Analysis of the climatic conditions for the study area and discarding the satellite images of the day the image was taken and if there were no good climatic conditions.
- Choice of the download platform, as well as the choice of programs to deal with them.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958171.

In order to complete the whole process by which the technique is applied, a number of tasks need to be carried out, which are mentioned below:

1. Planning: search to achieve the best possible results for each case study through the optimization of the following phases of the work.

2. Download data: choice of image download source for each particular case study as well as the images to be used.

3. Processing: work by which the results will be obtained.

5. Results: evaluation of the final product, and decision making based on it.

2.5.15.5 Interfaces and Connections

In satellites' case, communications between components is not necessary, but data storage in file repositories it is. For that, interfaces and ingestion methods are needed.

The information is needed in time to allow the infrastructures monitoring, so it has to be implemented a service which collects the satellite data from their allocation. This data transference from the satellite imagery owner to the platform is done through a SFTP protocol. Once the images are available in the platform, can be used by the services in charge of their management.

Another services has to be implemented in order to allow:

- Data edition, including image selection, selection of the domain and image processing.
- Data visualization and analysis.

2.5.15.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.15.6.1 Personnel

Human resource	**Cost (€)**	**Unit**
Engineer	40	Hour
Developer	40	Hour

Table 2.105 – Human resources for Remote sensing technique

2.5.15.6.2 Material resources

Material resource	**Cost (€)**	**Unit**
High-Resolution Satellite Imagery Ordering	6950	Image
Processing software	0	Day
High performance computer	12	Day
Storage hardware	0,05	GB

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Table 2.106 – Material resources for Remote sensing technique

The elements are not bought, so there are no amortisation costs calculated.

2.5.15.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	selection of the type of images necessary for the case study, their quantity and optimal dates for the analysis	8	Capturing day
Download data	selection of images used and full download time	24	Capturing day
Processing	image processing and implement algorithms developed for monitoring	360	Capturing month
Results	evaluation and decision making (presentation of results to the client)	24	Capturing day

Table 2.107 – Duration of tasks in Remote sensing technique

Task	Resource	Hours
Selection of the type of images necessary for the case study, their quantity and optimal dates for the analysis	High performance computer, Processing software, Engineer and Developer	8
Selection of images used and full download time	Storage hardware, High performance computer, Engineer	24
Image processing and implement algorithms developed for monitoring	Storage hardware, High performance computer, Processing software, Engineer and Developer	360
Evaluation and decision making (presentation of results to the client)	Storage hardware, High performance computer, Processing software, Engineer	24

Table 2.108 – Resources used in Remote sensing technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.15.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
High Resolution Satellite Image Ordering	Day	1,00	6.950,00 €	6.950,00 €	13,00%	903,50 €	6%	417,00 €	8.270,50 €
Processing Software	Hour	392,00	0,00€	0,00€	13,00%	- €	6%	- €	- €
High Performance Computer	Hour	416,00	12,00€	4.992,00 €	13,00%	648,96 €	6%	299,52 €	5.940,48 €
Storage hardware	GB	0,50	0,05€	0,03€	13,00%	0,00 €	6%	0,00 €	0,03 €
Engineer	Hour	416,00	40,00€	16.640,00€	13,00%	2.163,20 €	6%	998,40 €	19.801,60 €
Developer	Hour	368,00	40,00€	14.720,00€	13,00%	1.913,60 €	6%	883,20 €	17.516,80 €
				31.360,00€		4.076,80 €		1.881,60 €	**51.529,41 €**

Table 2.109 – Breakdown of costs and benefits for the budgeting of Remote sensing technique

2.5.16 Surface Measurement

2.5.16.1 Purpose and main features

Surface measurements are designed for assessment of concrete elements with the objective of improve maintenance planning and works. Surface measurements tests allways are destructive or semi-destructive and in all cases small repairs will be usually necessary to avoid cracking or other defects. When surfaces measurements are performed regularly, they collaborate in the prevention of degradation processes to facilitate the implementation of preventive operations. With this objective, they allow the identification of important characteristics of different structural elements of bridges and tunnels, including compressive strength and hardness.

Despite this technique is not designed for the evaluation of a specific element, it is possible to applied it to different elements such as:

- Beams.
- Slabs.
- Columns.
- Piers.
- Abutment walls.

This technique can be applied directly on the facility and its features and results vary depending the different method used for application. There are the following methods for surface measurement:

- Schmidt hammer test/Rebound test for evaluate damages processess such as corrosion and carbonation via the rebound number.
- Windsor probe test/Penetration test to stimate the concrete strength.
- Pull-out test to determine strength parameters.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

One technological barrier for this technique, independently of the selected procedure, is that is not possible to substitute the presence of the operator to perform the test.

2.5.16.2 Scenarios definition

Surface measurements are applicable to both bridges and tunnels without any special consideration derived of the infrastructure type. However, there are different scenarios for the surface measurements depending on the method used and some characteristics of the materials evaluated.

If the selected method is the Schmidt Hammer test, there are different options:

- Depending the thickness, type N for thickness greater than 10 mm and type L for values smaller than 10 mm.
- Type N for structural elements with a thickness greater than 10 mm.
- Type L for structural elements of material with thickness smaller than 10 mm.
- Concrete type: fresh low strength (1-5 MPa, 5-10 Mpa), normal (10-30 MPa, 30-70 MPa) or high strength concrete (70-100 MPa).

If it is used the Windsor probe test, there are two equipment types depending on the application:

- Windsor system: one option with a probe for lightweight, low density concrete, and another wih a probe for standard mix designs.
- Probe material: one for concrete with strength greater thatn 110 MPa and another for those with strength smaller than 110 MPa.
- Power setting: low power or standar power.

In the case of the pull-out test, there are no different scenarios to evaluate.

2.5.16.3 Technology characteristics

There are different results and characteristics depending on the type of test performed. Due to this variety of characteristics of the different methods of acquire surface measurements, the type of measurements taken are heterogeneous. There are both manual and automatic measures, as well as mechanical and digital measurements. Despite this heterogeneity, there is one feature common to all methods and that is that the measurements must be performed statically.

The expected outputs for this methods are not the same for each method. While for the Schmidt Hammer test the result acquired is a list of number with rebound values, the Windsor probe test returns a list with the compressive strength values and the Pull-out test only return the force value needed to pull out the steel anchor for selected tested areas.

Due to the fact that the results of each method are different, the interpretation of those results and the accuracy are also different in each case.

- In the Schmidt Hammer test, compressive is strength estimated from the rebound number obtained in the test by using the correlation curves provided by the manufacturer where it is shown the relation between both values. The result value interpretation include its validation by taking an average of 8-10 rebound numbers eliminating the extreme values (those too high or too low) and the read off of the compressive strength with use of the selected conversion curve. Regarding its accuracy, is dependant on the hammer type.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- In the Windsor probe test, the estimation of the concrete strength is done from the surface hardness of the concrete element. The penetration resistance is computed by measuring the exposed length of probes driven into concrete and, then, using the relationship between penetration resistance and concrete strength. This relationship must be established for a particular equipment (an useful help for this purpose are statistical methods). About the accuracy of this test, it depends on the type of system configuration performed.
- In the pull out test, the strength parameters are determined from the force value generated by the test and via the usage of calibration curves or correlation with other non-destructive methods. Mean and standard deviation of the set of pull-out test are also determined. This method accuracy can be more than twice as accurate compared with non-destructive surveys.

2.5.16.4 Metodology: phases and tasks

There are some relevant aspects to consider to perform surface measurements in a appropriate way. These are included the following aspects for the case of the Schmidt Hammer test:

- Avoid rough surfaces.
- The hammer has to be rigidly held to avoid a reduction in the rebound number due to any movement caused by the impact of the hammer.

If the selected test is the Windsor probe test, the aspects to take into account are:

- Usage of specially frames to relieve the structure from the load and avoid surface damaging.
- Knowledge of the aggregate hardness.

If pull-out test is the chosen option, the aspects to consider are:

- The test should be preceded by the reinforcement location, the removal of corroded concrete and the surface smoothening.
- Anchor axis must be at least 100 mm from the edges and 50 mm from the reinforcement inserts.
- On a single element, tests are performed in at least 5 measurements places.

To complete the test, there are some tasks to perform which are mention below:

1. Collection of the samples.
2. Calibration of the equipment. It is different for each method and based on manufacturer indications.
3. Measurement.
4. Analysis of the results.
5. Validation by using correlation curves.

2.5.16.5 Interfaces and Connections

The data obtained with this technique can be collected manually by the operator by reading in the hammer display the rebound number. However, it is possible to send the data from the hammer to a PC via an usb connection or bluetooth. Then, the data can be stored in the PC to be accesible by the service in charge of manage them. This service allows the data management (modification, sorting, etc).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

It is possible to use a web server for the data management, so in this case a protocol for transfering the data from the computer to the webserver is needed such as TCP/IP.

2.5.16.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.16.6.1 Personnel

Human resource	Cost (€)	Unit
Civil engineer	8,05	Hour

Table 2.110 – Human resources for Surface measurement technique

2.5.16.6.2 Material resources

Material resource	Cost (€)	Unit
Schmidt hammer (simple model)	344,14	Device
Schmidt hammer (average model)	2043,34	Device
Schmidt hammer (advanced model)	3871,59	Device
Windsor probe	3049,11	Device
Pull-out tester (digital pull-out test kit)	4829,23	Device
Pull-out tester Pro 25 kN(confirm theholding power of anchors)	3273,75	Device

Table 2.111 – Material resources for Surface measurement technique

The amortisation cost of each device is calculated on the basis of its purchase price:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
Schmidt hammer	simple	344,14	10,00%	2	70	2,21€
Schmidt hammer	average	2043,34	10,00%	2	70	13,14€
Schmidt hammer	advanced	3871,59	10,00%	2	70	24,89€
Windsor probe		3049,11	10,00%	2	70	19,60€
Pull-out tester (digital pull-out test kit)		4829,23	10,00%	2	70	31,05€
Pull-out tester Pro 25 kN(confirm theholding power of anchors)		3273,75	10,00%	2	70	21,05€

Table 2.112 – Amortisation of materials used in Surface measurement technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.16.6.3 Performance

Phase	Task	Duration (hours)	Unit
Schmidt hammer - preparation	Situational sketch of the tested elements of the bridge	0,5	3 elements - cornice, wall and deck plate
Calibration of the hammer	Performing a calibration check	0,5	does not depend on the size of the structure
	Performing a reset	0,2	does not depend on the size of the structure
Initialization	Smoothening of the concrete surface (for point measurement)	0,5	3 elements - cornice, wall and deck plate
Measurement	Determining the rebound number	0,5	3 elements - cornice, wall and deck plate
Reporting	Determining the hardness of the surface	0,5	3 elements - cornice, wall and deck plate

Table 2.113 – Duration of tasks in Surface measurement technique

Task	Resource	Hours
Situational sketch of the tested elements of the bridge	Civil Engineer, Schmidt hammer	0,5
Performing a calibration check	Civil Engineer, Schmidt hammer	0,5
Performing a reset	Civil Engineer, Schmidt hammer	0,2
Smoothening of the concrete surface (for point measurement)	Civil Engineer, Schmidt hammer	0,5
Determining the rebound number	Civil Engineer, Schmidt hammer	0,5
Determining the hardness of the surface	Civil Engineer, Schmidt hammer	0,5

Table 2.114 – Resources used in Surface measurement technique tasks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.16.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Schmidt hammer (simple model)	Day	1,00	46,28€	46,28€	13,00%	6,02 €	6,00 %	2,78 €	55,07 €
Windsor probe	Day	1,00	19,60 €	19,60€	13,00%	2,55 €	6,00 %	1,18 €	23,32 €
Pull-out tester (digital pull-out test kit)	Day	1,00	31,05 €	31,05€	13,00%	4,04 €	6,00 %	1,86 €	36,95 €
Pull-out tester Pro 25 kN(confirm theholding power of anchors)	Day	1,00	21,05 €	21,05€	13,00%	2,74 €	6,00 %	1,26 €	25,05 €
Civil Engineer	Hour	2,70	8€	21,74€	13,00%	2,83 €	6,00 %	1,30 €	25,86 €
				139,72€		18,16 €		8,38 €	**166,26 €**

Table 2.115 – Breakdown of costs and benefits for the budgeting of Surface measurement technique

2.5.17 Water Penetration Test / Permeability Test

2.5.17.1 Purpose and main features

The water penetration test is designed for the determination of the resistance or durability of concrete extracted elements of structures exposed to the water flow, including bridges and tunnels. Furthermore, this technique main purpose is that the water penetration level is a good indicator of the quality in terms of durability under hydrostatic pressure.

Its application is very useful for specific parts of the structure that are particularly vulnerable to corrosion and chemical attack. Although it is not used for monitorings, it is a good tool to use in maintenance works.

There are different parameters obtained with water penetration test, but only the water penetration depth is quantitatively evaluated, being its units mm. The other parameters/damages effects, that are qualitatively assessed, include cracks, holes, loss of section, rupture, deformation and wire break.

The test can be performed automatically in different research cycles allowing the simultaneously testing of several samples. However, guidelines for test performance are not enough precise in term of age of the sample at which test should begin, nor the cut-off age of concrete that can be tested. That implies that it is possible to obtain different results.

2.5.17.2 Scenarios definition

The test is performed in a laboratory, so there is no influence of the environment and the characteristics of the test and how it has to be performed do not change depending materials nor type of structures, so it not applies to define particular scenarios.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.17.3 Technology characteristics

Water penetration test allows to the obtention of the water penetration depth in laboratory conditions. The test is performed to take manual, mechanical and statical measures, obtaining as a result a numeric value of the maximum depth of penetration, expressed in mm, after different days period for the cross-section of the drenched area. After that, the obtained results can be compared between different concrete classes. For this purpose, before the analysis it is necessary to collect samples for destructive testing beforehand, by removing the sample from the infrastructure.

2.5.17.4 Metodology: phases and tasks

There are some criteria to follow in water penetration test to ensure that the results obtained are valid:

- The water pressure should be applied on the surface which was in contact with the form.
- For samples taken from existing structures, the sample area should be cleaned with a steel brush.
- The depth of water penetration into the sample decreases over the time of the samples.
- For fresh concrete, the age of the sample must be of 28 days at least.

Another aspects to take into account for the test performance are:

- There should be safe to access to the part of the existing concrete structure where sample to collect is located.
- The formation of weathering crust from mineralogical changes on the exposed surface will influence measurements of the water permeability.

There are some characteristics of the samples to think about in the preparation of the test. One feature is that there are different types of samples which can be used (cubic, cylindrical and rectangular). Another characteristic is the minimum area size for water pressure application, which can not be less than 150 mm.

The way of performing the test is standardized in the standard EN 12390-8:2019. To ensure that the test generate valid results, the test should be carried out on at least three samples to identify and reject any outliers, because apply only on a single sample could lead to a possible disqualification of a concrete batch that meets the requirements.

The workflow of the test is divided in different phases, including the following:

1. Sample collection from the structure.
2. Measurement.
3. Quality control.
4. Analysis.

2.5.17.5 Interfaces and Connections

The testing process is carried out manually without the use of electronic devices, except a balance. It could be possible to automate partially the test, not the sample collection and decision making but the placement of the samples and the immersion time. For this reason, the definition of interfaces and connections is limited in this case to the definition of a user interface and its related services. The implementation should take into account the following characteristics:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- The software may be allocated in a local medium as a computer or being hosted in a cloud server.
- The services must allow the users to add new data to the database and manage them (sorting, deleting or editing) to facilitate the data analysis.
- The data transferred is numeric, so an appropiate protocol in this case is HTTP.

2.5.17.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.17.6.1 Personnel

Human resource	Cost	Unit
Laboratory Technician	19,34	Hour
Laboratory Specialist	21,94	Hour

Table 2.116 – Human resources for Water Penetration Test / Permeability Test

2.5.17.6.2 Material resources

Material resource	Cost	Unit
Pressured permeability tester	4293,91	Device

Table 2.117 – Material resources for Water Penetration Test / Permeability Test

The amortisation cost per day of the device used is as follows:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
Pressured permeability tester	Not specifed	4.293,91€	10,00%	2	50,00	38,65€

Table 2.118 – Amortisation of materials used in Water Penetration Test / Permeability Test

2.5.17.6.3 Performance

Phase	Task	Duration (hours)	Unit
Preparation	Collection of the concrete samples	1	One structural element
Initialization	Preparation of the samples - removing outer coating, cleaning	0,5	One structural element
Measurement (laboratory)	Placing the samples in the testing machine	0,1	-

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	Starting the test - water pressure acts on concrete surface	72	For batch of samples
Finalization	Samples split in half	1	For batch of samples
Analysis	Marking depth of the penetration of water	1	For batch of samples
Reporting	Preparing the report	1	For batch of samples

Table 2.119 – Duration of tasks in Water Penetration Test / Permeability Test

Task	Resource	Hours
Collection of the concrete samples	Laboratory Technician	1
Preparation of the samples - removing outer coating, cleaning	Laboratory Technician	0,5
Placing the samples in the testing machine	Laboratory Technician	0,1
Starting the test - water pressure acts on concrete surface	Laboratory Technician	72
Samples split in half	Laboratory Technician	1
Marking depth of the penetration of water	Laboratory Specialist	1
Preparing the report	Laboratory Specialist	1

Table 2.120 – Resources used in Water Penetration Test / Permeability Test tasks

2.5.17.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Pressure permeability tester	Day	1,00	38,65€	38,65€	13,00%	5,02 €	6,00%	2,32 €	45,99 €
Laboratory technician	Hour	74,60	19,34€	1.442,76 €	13,00%	187,56 €	6,00%	86,57 €	1.716,89 €
Laboratory specialist	Hour	2,00	21,94€	43,88€	13,00%	5,70 €	6,00%	2,63 €	52,22 €
				1.525,29 €		198,29 €		91,52 €	**1.815,10 €**

Table 2.121 – Breakdown of costs and benefits for the budgeting of Water Penetration Test / Permeability Test

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.18 Water Resistance/ Absortion Test

2.5.18.1 Purpose and main features

The deterioration of concrete structures is due, among other causes, to water influence. This influence is produced not only by internal reactions of reinforced concrete structure materials, but also by the activation of the chemical substances present in the environment which cause the chemical reactions to progress, contributing to the deterioration of the structures. For this purpose, the measurement of the water resistance allows to determine the space of pores and absorption rate in the concrete. This technique acts also as a determination of the effectiveness of the agents used to secure building materials from the water influence.

Due to this characteristics explained above, water resistance is a technique used for help in maintenance works in both bridges and tunnels. It is particularly useful apply this technique for testing pavements slubs, curbs and bricks.

The water resistance test can be combined with Scanning Electron Microscope observation. With that it is possible to perform, in a simple way and without specific qualifications for the operator, an evaluation of spalling and cracks for the infrastructures. Moreover, the test can be performed on-site and in laboratory.

However, it should be noted that this test has a short duration compared to what might occur under long period conditions and assumes that all gained weight is due to water.

2.5.18.2 Scenarios definition

The main idea of the test is to detect the increase of the mass of the testing element, assuming all the gained weight is due to water absorption. For that, only one surface of the element has to be exposed to water. Furthermore, the test can be performed on-site or in a laboratory, with a small difference. If the test is performed on-site, the volume of water absorbed has to be detected within a specified period of time.

2.5.18.3 Technology characteristics

Water resistance test is based on performing a static and local measurement for short-term investigation, so there will be only one measurement at each time. This measurement may be repeated at specified time intervals. Each measurement shall be acquired manually, mechanically and statically.

The output generated in the test is numeric value which represents the absorption coefficient, expressed as an increase in the weight percentage or a volume absorbed. His process entails an accuracy dependant on the preparation stage and the accuracy of the balance used.

The water absorption test workflow and characteristics is normed by two standards: RILEM Test Method – Test No.11.4 and ASTM C 642-90.

2.5.18.4 Metodology: phases and tasks

The material affects the required dimensions for the collected samples:

- Concrete: cubic samples of 100 mm x 100 mm.
- Stone: cubic samples of 70 mm x 70 mmm or 50 mm x 50 mm.
- Cement-lime: bars of 40 mm x 40 mm x 160 mm.

To perform the test in an adequate way, some tasks have to be carried out, in the following order:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

1. Initialization: collection of the sample, with the required dimensions relative to the material, from the place of interest.
2. Preparation: it involves sample drying followed by cooling to ambient temperature, measurement of samples dimensions, their placement in the cuvette with water, registering the hour, and covering the cuvette with foil.
3. Measurement (after specified intervals). It includes removing the samples, delicate drying, weighting directly after taking out, replace the sample again int the cuvette until next period of weighting, determine the mass change and water absorption rate.
4. Reporting with the conclusions after the test.

2.5.18.5 Interfaces and Connections

The testing process is carried out manually without the use of electronic devices, except a balance. It could be possible to automate partially the test, not the sample collection and decision making but the placement of the samples and the immersion time. For this reason, the definition of interfaces and connections is limited in this case to the definition of a user interface and its related services. The implementation should take into account the following characteristics:

- The software may be allocated in a local medium as a computer or being hosted in a cloud server.
- The services must allow the users to add new data to the database and manage them (sorting, deleting or editing) to facilitate the data analysis.
- The data transferred is numeric, so an appropiate protocol in this case is HTTP.

2.5.18.6 Resources

The following is a breakdown of the human and material costs for each technology, in the case of equipment, its amortisation, the estimated performance for each task and a balance of the expected costs and benefits.

2.5.18.6.1 Personnel

Human resource	Cost	Unit
Laboratory Technician	20,48	Hour
Operator	15	Hour

Table 2.122 – Human resources for Water Resistance/ Absorption Test

2.5.18.6.2 Material resources

Material resource	Cost	Unit
Comissioning a test to a laboratory	166,75	One batch of samples

Table 2.123 – Material resources for Water Resistance/ Absorption Test

Not applicable. to estimate the amortisation costs because the test is commisioned to a laboratory but no equipment or device is bought.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

2.5.18.6.3 Performance

Phase	Task	Duration (hours)	Unit
Initialization	-	1-5	Depends on the number of samples
Preparation	-	1	-
Measurement	Leaving the samples subjected to ingress of water	24	-
Reporting	.-	1	-

Table 2.124 – Duration of tasks in Water Resistance/ Absorption Test

Task	Resource	Hours
Initialization	Operator	1-5
Preparation	Laboratory Technician	1
Measurement	Laboratory Technician	24
Reporting	Laboratory Technician	1

Table 2.125 – Resources used in Water Resistance/ Absorption Test tasks

2.5.18.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
Comissioning a test to a laboratory	Hour	1,00	166,75€	166,75€	13,00%	21,68 €	6,00%	10,01 €	198,43 €
Laboratory technician	Hour	26,00	20,48€	532,48€	13,00%	69,22 €	6,00%	31,95 €	633,65 €
Operator	Hour	5,00	15,00€	75,00€	13,00%	9,75 €	6,00%	4,50 €	89,25 €
				774,23€		100,65 €		46,45 €	**921,33 €**

Table 2.126 – Breakdown of costs and benefits for the budgeting of Water Resistance/ Absorption Test

2.5.19 Weight in Motion Systems (WIM-Systems)

2.5.19.1 Purpose and main features

Weight in motion systems automate traffic data collection and prevent the overload of the structures with the objective of optimize the infrastructure maintenance planning as well as tracking special transports, reduce risks and monitoring structural health of infrastructures. Its purpose also is related to the fact that load of vehicles contribute to the deterioration of roads and bridges, so it is necessary to control the infrastructure overload with accurate scales. However, due to the fact that is a new technology, actually the main problem with WIM systems is the lack of standardization.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

WIM systems are designed for monitoring the whole structure of infrastructures as bridges, highways, motorways or railways.

The system can be mounted with a combination of different sensors, being the typically sensors used the following:

- Bending plates.
- Load cells.
- Quartz piezo sensors.
- Polymer piezo sensors.
- Strain gauge strip sensors.
- Telecamera

Through the usage of WIM systems can be evaluated parameters as overloading of the infrastructure, based on the weight of the vehicles, the tire impact forces, strain forces and the vehicles speed. The forces are expressed in N (Newtons), the weight in T (tons) and the speed in km/h.

2.5.19.2 Scenarios definition

The usage of WIM system is dependant on the infrastructure types and the application or technology to use:

- It is not applicable for tunnels.
- Static weighing of road vehicles. These results are usually used as reference values for calibrating WIM system.
- WIM systems for bridges. They are dynamic weighing systems where the sensors are embbeded in the roadway surface or placed under/on the bridge deck.
- High-Speed WIM systems. They weigh in open traffic at normal speed and under free-flow conditions.
- Low-Speed WIM systems. The weighing is placed in a dedicated controlled area, normally outise the main traffic lane, under controlled conditions.
- Dynamic onboard WIM systems that are fitter to vehicles. Such a system will constantly measure the weight, axle and wheel loads while vehicle continues its movement.
- Rail Weight-in-Motion systems consistis in a dynamic weighing of rail vehicles to determine the weight of wagons.

WIM systems are not depending of the material of the structure to be analyzed and are designed for monitoring whole structures as bridges, highways, motorways or railways.

Taking into account the road characteristics and environment, the road surface needs to be within certain tolerances to obtain the highest accuracy. These tolerances are detailed within the EU document COST 323.

2.5.19.3 Technology characteristics

With these technologies is possible to take automatically digital measurements in motion. There will be several measurements acquired at the same time and these measurements have to be performed and managed in real time 24/7.

The accuracy is referred to several accuracy classes defined in the standard COST 323. The accuracy obtained by the system is influenced by the calibration in both initial and life cycle

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

phases. However, accuracy could not be evaluated on the agreggated data. Moreover, the accuracy levels depend on the requirements and the application.

The WIM system is composed by a basic software, a server software and the equipment in charge of acquire the data in the suitable conditions and manage the communications(videograbber, cameras, GPS receiver, GPRS /UMTS modem, etc.).

2.5.19.4 Metodology: phases and tasks

Prior to other requirements, to use a WIM system there are some general requirements to analyze as the following:

- Road selection, including the road type and its geometry or the road areas to avoid (traffic lights, toll stations, etc).
- Pavement characteristics.
- Environmental conditions.
- Legal issues.

Measurements are sensitive to pavement and environmental conditions (air temperature, humidity, wind, precipitation intensity, etc). Furthermore, there are some additional criteria to be considered for the bridges due to their particularities, such as bridge type, length or pavement evenness.

2.5.19.5 Interfaces and Connections

The system is formed by several components, both hardware and software, interconnected in a proper way to ensure communications.

The execution of the interface will be in a webserver, so are needed services to:

- Store the data in the cloud.
- To execute the different parts of the application, including the visualization of the results.

In order to control the performance of the technique and store the data, the following connections between the different nodes of the system are noticed:

- The embbeded sensors, such as bending plates, are connected via a modem GPRS/UMTS.
- The camera connection will be by Gigabit Ethernet, independently the connection is wireless or not.
- The IP illuminator is controlled by the camera by a wireless connection based on Gigabit Ethernet.

The protocol used for all the componets is TCP/IP.

A user interface based on a web service has to be implemented to allow the user to not only visualize data but also to manage them with actions such as sorting, delete some of them, etc.

2.5.19.6 Resources

There are several resources, both in terms of humans resources and material resources, that affects to the performance of the technique and the economical result of it.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

2.5.19.6.1 Personnel

Human resource	Cost (€)	Unit
Security Personnel	16	Hour
Civil Engineer	23,06	Hour
Software Engineer	29	Hour
Road Inspector	26	Hour

Table 2.127 – Human resources for WIM-Systems

2.5.19.6.2 Material resources

Material resource	Cost (€)	Unit
Implementation of the Low-Speed WIM system	26951,70	One station/per truck
Implementation of the High-Speed WIM system	64315,88	Per traffic lane
Hardware for High-Speed WIM	1167,91	Per truck
Hardware for Low-Speed WIM	539,03	Per truck

Table 2.128 – Material resources for WIM-Systems

The amortisation cost per day of the materials used is as follows:

Product	Model	Price	% residual	Year	Uses/Year	Amortisation/day
WIM System	Low-Speed	26.951,70€	10,00%	3	100	80,86€
WIM System	High-Speed	64.315,88€	10,00%	3	100	192,95€
Hardware WIM System	Low-Speed	1.167,91€	10,00%	2	100	5,26€
Hardware WIM System	High-Speed	539,03€	10,00%	2	100	2,43€

Table 2.129 – Amortisation of materials for WIM-Systems

2.5.19.6.3 Performance

Phase	Task	Duration (hours)	Unit
Planning	Purpose of application	0,5	Road lane
Planning	Selection of the location	0,5	Bridge
Planning	Selection of the road section	0,5	Bridge

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Preparation	Visual Inspection	1-2	Road lane
Preparation	Sensor Instalation	1-2	Road lane
Maintenance period	Two weeks between first instalation and calibration	336	Bridge
Calibration	System calibration	2	Road lane
Maintenance period	Two weeks between first calibration and the acceptance period	336	Bridge
Acceptance tests	Approving tests before remote monitoring	24	Road lane
Monitoring	Remote monitoring	No limit	Bridge
Evaluation	Evaluation of the weighing results	2	Road lane

Table 2.130 – Duration of tasks in WIM-Systems

Task	Resource	Hours
Purpose of application	Road Inspector	0,5
Selection of the location	Road Inspector, Security Personnel	0,5
Selection of the road section	Road Inspector, Security Personnel	0,5
Visual Inspection	Civil Engineer	1-2
Sensor Instalation	Civil Engineer, Software Engineer	1-2
Maintenance period	Software Engineer (supervision)	336
Calibration	Software Engineer	2
Maintenance period	Software Engineer (supervision)	336
Acceptance tests	Software Engineer, Road Inspector	24
Monitoring	Road Inspector	No limit
Evaluation	Road Inspector	2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Table 2.131 – Resources used in WIM-Systems tasks

2.5.19.6.4 Cost/benefit analysis

Resource	Unit	Units	Cost/Unit	Cost	%O	O	% B	B	Budget
WIM system (Low-Speed)	Day	1,00	80,86€	80,86€	13,00%	10,51 €	6,00%	4,85 €	96,22 €
WIM system (High-Speed)	Day	1,00	192,95€	192,95€	13,00%	25,08 €	6,00%	11,58 €	229,61 €
Hardware WIM (Low-Speed)	Day	1,00	5,26€	5,26€	13,00%	0,68 €	6,00%	0,32 €	6,25 €
Hardware WIM (High-Speed)	Day	1,00	2,43€	2,43€	13,00%	0,32 €	6,00%	0,15 €	2,89 €
Security personnel	Hour	1,00	16,00€	16,00€	13,00%	2,08 €	6,00%	0,96 €	19,04 €
Civil engineer	Hour	4,00	23,06€	92,24€	13,00%	11,99 €	6,00%	5,53 €	109,77 €
Software engineer	Hour	700,00	29,00€	20.300,00 €	13,00%	2.639,00 €	6,00%	1.218,00 €	24.157,00 €
Road inspector	Hour	27,50	26€	715,00€	13,00%	92,95 €	6,00%	42,90 €	850,85 €
				21.107,24 €		2.743,94 €		1.266,43 €	**25.471,62 €**

Table 2.132 – Breakdown of costs and benefits for the budgeting of WIM-Systems

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

3. Data pre-processing (quality assurance)

3.1 Introduction

The compliance with certain steps and the verification of defined quality parameters allow to know the correct collection of data, detecting information that will not provide useful or valid results in the subsequent processing. The quality indicators shall be specific for each of the parameters through which each sensor provides information and can be known live during the acquisition or in a subsequent analysis of the acquired information.

This section will cover in more depth the procedures used in the acquisition or pre-processing process to make, depending on the technique used, quantitative or qualitative assessments of the error committed.

In some techniques there is no required data preprocessing due to the nature of the technique and their ouput data.

3.2 Guidelines for safe and efficient data monitoring

In preprocessing, the basic workflow is as follows:

a. Specification is given to a tool with a dataset on which to act.
b. The tool performs the preprocessing of the data unattended.
c. The resulting report is analysed to determine whether or not to continue the data processing.

This tool must meet the following characteristics:

- It must work unattended and automatically.
- Implement parallel data processing.
- The output will be a report containing enough information to determine whether the data quality meets the requirements for further processing.

This tool must implement the necessary software for the conversion of raw sensor data into interpretable data, as well as software for corrections to be made to the data if necessary.

3.3 Survey technologies

3.3.1 Acoustic Emission (AE)

3.3.1.1 Evaluation of parameters for quality control

The validation of the data acquired by this technique can be done by the usage of a cluster processor. It clusters datasets taking into account some attributes and color codes. The processor cluster local densities of acoustic emission sources, providing a measure of the activity of the acoustic emission cluster.

Another validation step is to ensure that the file is not corrupted. For this purpose, there are two aspects to check:

- The software is able to extract correctly the set of features.
- There are no data missing or visually inconsistent. The check for missing data can be performed directly by the software by comparing the received data with the expected data.

Parameters to be checked for quality control are:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - Pre-amplifying units characteristics - Gain - Signal distortion

Table 3.1 – Parameters for quality control in AE technique

3.3.1.2 Expected outputs and standards

The data provided by the acoustic emission sensors will be received in a standardized file format. The software for the acoustic emission technique have to comply with EN13477-1 and EN13477-2.

The expected outputs for this technique is a database file with one of the following extensions:

- .pridb for the parametric data, status data and user input data.
- .tradb for the transient data.

Within the list of parameters received from this technique, there are the following:

- Graph witih the signal at the output of the sensor (amplittude on the sensor on dB related with time in seconds).
- Number of signals.
- Signal energy,
- Burst signal energy.
- Rise time.
- Duration.
- Number of positive threshold crossings between the start of hit and end of.

3.3.1.2.1 Evaluation of methods for data preprocessing and correction

3.3.1.3 Preprocessing

The binary generated file has to be converted to the free file format based on SQLite, so files with a PRI format will be converted into a file with a .pridb extension and files with a TRA format will be converted to a file with a .tradb extension.

3.3.1.4 Data correction

Correction	Description
High-pass filter	Attenuates signals with frequencies lower than the cutoff frequency.
Signal amplification	It has to be applied after the high-pass filter.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

AERMS	Demoludation via Root Mean Square method.
Wrong data identification	It depends on the structure of the software. Algorithms eliminate data based on some boundary parameters and if the collected data do not meet the requirements, they are out of the database. Visual AE can be performed for data analysis in on-line and off-line modes. Frontend filter (logical filter) rejects data from unimportant time periods or out of logical filter conditions.

Table 3.2 – Data correction in AE technique

3.3.2 Aerial UAV. Optical Payload

3.3.2.1 Evaluation of parameters for quality control

The UAVs can operate with different sensors onboard so there are different possible parameters which can affect the quality of their measurements.

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day
Positioning system	- Geodetic reference system - Altitude and coordinates format - Cartographic projection - UTM zone - Trajectory resolution - Reference stations
Imagery	- Transverse field of view - Sensor calibration - Automatic exposure control - Sensor spectral resolution - Radiometric resolution - Photogrammetric window - Pixel size and flying height - Longitudinal overlay - Transverse overlay - Camera vertical deviation - Verticality differences between consecutive frames - Changes of course between consecutive frames - Area to be overlaid - Orientation (direction of images) - Noise - Burned areas
Lidar	- Transverse field of view - Scanning frequency - Pulse frequency

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

	- Spatial resolution. Average density - Sensor calibration - Multiple intensity radiometric resolution - Maximum number of returns per pulse - Photogrammetric window - UAVs speed at the time of data capture - Scanning height - Transverse overlay - Deviations from the vertical of the sensor - Covered area - Noise - Gaps
Radar	- Location - Size - Shape - Color - Height - Depth - Overlay - Wavelength - Incidence angle - Covered area

Table 3.3 – Parameters for quality control in Aerial UAV technique

3.3.2.2 Expected outputs and standards.

Because different sensors can be mounted on the UAVs, such as cameras, lidar or radar, the expected outputs can be of different types of information, including:

- Numeric data.
- Alphanumeric data.
- Images.

The above data could be stored in formats as:

- Plane text file.
- Binary files.
- Database.
- Images in formats as RAW, TIFF or JPG.

There are no any particular standard described for UAVs.

3.3.2.3 Evaluation of methods for data preprocessing and correction

3.3.2.3.1 Preprocessing

Raw sensor data has to be converted into standard formats during the preprocessing. Taking into account that the UAVs can be embbeded with different sensors, preprocessing has to combine the information received from these different sources. The main operation is to add the positioning information to the image or point cloud data to have the georreferenced data.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- **Trajectories**

Trajectory data given by inertial measurement units (IMU) are often collected in a binary format specific to the equipment used and cannot be immediately interpreted or converted to waypoints. This is because these files do not contain the points of these trajectories already processed, but a set of logs with observations and ephemerides from the satellites, detections from the inertial sensors, sensor status report, accuracy of the solution at each moment, etc., so that an external system can later reconstruct the trajectory accurately based on this information.

To obtain the trajectory, information not known to the sensor at the time of collection shall be used, such as GNSS information from a fixed base antenna or information from a nearby geodetic station available online, which will provide deviations in the satellite observations at the time of capture. Usually the files obtained will be in RINEX format, otherwise they may need to be converted before proceeding with the trajectory acquisition.

The pre-processing of the trajectory will normally be done in the software offered by the manufacturer of the IMU employed, although it might be possible to use other software that accepts the formats or logs collected by the equipment. In the software, a new project will be created with the data generated by the IMU during the acquisition and the information of the bases used in RINEX format (either own bases placed during the acquisition or permanent stations). Then, the required calibration data (distance and angular offsets between antenna, IMU, UAV, DMI...) must be indicated to the program, with the precision with which they have been measured.

After this, a trajectory file with waypoints will be obtained in the desired format from those offered by the software used. These can be binary files with a known structure and therefore recognisable by other programs (such as Applanix SBET), ASCII files with header and tabulated trajectory data or KML files widely recognisable by GIS software, among others. Depending on the type of output file chosen, the software may vary the units of some of the data (for example, giving sexagesimal angles or radians), which must be taken into account during the design of the procedure.

- **Images**

The images captured by the UAVs cameras are saved in the chosen image format, either a standardised format such as TIFF or JPEG or a raw format convertible by software offered by the manufacturer. In the case of RGB images taken by a 360° panoramic imaging camera, the output files will generally be produced in a proprietary format containing each file several images. Using the software or API given by the manufacturer it is possible to obtain both the panoramic images or an individual image for each camera, as desired.

Although cameras store in the metadata of the images obtained a timestamp for each image, this timestamp is generally not sufficiently accurate or the sensor time may not be correctly synchronised with the other equipment. It is therefore advisable to have a record of the number of images captured during the scan. If the triggers have been taken from a control system or from the IMU, there will be a file with both the triggers taken and the strobes received (a signal from the camera indicating the time at which the image was captured). In the case that it is the camera itself that performs the triggers by time, only the strobes record will be available. In any case, the strobes file will be the only one necessary, as it will contain a precise timestamp of the acquisition of each image, sorted by acquisition time.

Some cameras have input for NMEA and PPS signals, so that the produced images already contain a GPS position either in the image metadata or in an additional XML file with the position of each image. However, since this position is based exclusively on GNSS information collected by an antenna, it is preferable to calculate the position of each image from its timestamp, crossing the data with the trajectory data and taking into account the offsets of the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

camera with the vehicle or IMU. Some cameras can calculate their orientation from a stabilisation system, in which case this orientation data can be also used for the calibration.

Once the timestamp, position and orientation of each image has been obtained, it is possible to modify the metadata of these images to record the calculated values, although it is always advisable to generate an XML file with the names or paths of the images and this data.

- **Point clouds**

The point clouds will generally consist of binary files which depending on the manufacturer will have a different structure. The manufacturers of each sensor provide the tools (software or API) and documentation necessary to generate a static point cloud around the centre of the lidar sensor.

To obtain a point cloud with each point georeferenced and in a standardised format, we must add the information obtained from the trajectory already pre-processed, available in a single file in the chosen format, as it has been explained above. In addition, since the position and orientation of the lidar will vary with respect to the position and orientation of the UAV or IMU (whichever has been used as a reference to generate the trajectory), it will also be necessary to have these lidar calibration data, which will consist on distance and angular offsets.

With this information it is possible to generate a point cloud taking into account the position of the UAV at the time of acquisition of each point. Since lidar sensors sample points in space at a much higher rate than the sampling rate of an IMU, it is necessary to interpolate the points in the trajectory, so the capture rate will define the accuracy of the cloud obtained in this step.

The generated cloud will preferably be generated in a standardised point cloud format such as LAS format, which can be opened by any point cloud reading or processing software or library.

3.3.2.3.2 Data correction

- **Images**

Correction	Description
Border noise removal	Remove low intensity noise and invalid data on scene edges.
Thermal noise removal	Reduce noise effects
Calibration	Converting digital pixel values to radiometrically calibrated SAR backscatter.
Speckle filtering	Reduce speckle.
Range Doppler terrain correction	Correct geometry distorsion using a digital elevation model to correct the location of each pixel.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Conversion to dB	Convert the unitless backscatter coefficient to dB by using a logarithmic transformation.
Histogram normalisation	Enhances the contrast of an image by normalising the histogram. For this, for each component of the RGB spectrum, the smallest value is shifted to 0 (black) and the largest to 255 (maximum), resulting in sharper differences between the colours in the image.
Histogram linearisation	Enhances contrast in images with dark areas usually due to backlighting. This is done by giving each intensity value the same probability of existing in the image, resulting in that the same number of pixels with each value exist. This effect can solve different problems than normalisation, but is more likely to generate false colours.
Radiometric corrections	Radiometric correction algorithms look for defects or artefacts in the images due to poor sensor calibration or particular atmospheric conditions. They are detected by studying patterns of pixels with a marked geometry and that contrast too much with the rest of the adjacent pixels, studying the image by bands. Depending on the radiometric correction method used or the size of the error found, some of these defects can be corrected by interpolation of neighbouring pixels.
Convolution filters	Some convolution filters are used to correct the sharpness of an image or to highlight its edges. They work like a mask transforming each pixel locally using information from its neighbouring pixels.
Low pass or interpolation filters	Low pass filters analyse images in the frequency domain, allowing only low frequencies. In this way, the image undergoes a process analogous to dilation by subtracting only those elements that occupy a larger surface area in the image. This could remove noise or grain from images.

Table 3.4 – Data correction for images in Aerial UAV technique

- **Point clouds**

Correction	Description
Decimated	Reduction of the number of total points in a point cloud by eliminating those considered most superfluous following a chosen algorithm. In some more complex decimation algorithms, triangulated ways of replacing several points with a single point are calculated so that the structures do not significantly change their geometry.
Noise filtering	Elimination of points from the point cloud that fall below the established accuracy parameters, considered as "noise". There are several filters that perform the selection of these points. These filters can be based, among other criteria, on: - Detection of isolated or atypical points whose source can be a reflection or a false return - Elimination of returns with a very low reflectivity.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	- Points at such a distance that the errors due to angular uncertainty become very large..
Normalisation	The aim of normalising a point cloud is to obtain a model of the terrain only. Therefore, normalisation algorithms work by elaborating a digital terrain model (DTM), which draws the real terrain curve, and eliminating those points that do not lie on it or even interpolating those that are close to it to correct them.

Table 3.5 – Data correction for point clouds in Aerial UAV technique

3.3.3 Fibre Optic Sensors (FOS)

3.3.3.1 Evaluation of parameters for quality control

The method used for the validation of the data generated by fibre optic sensors depends on the theoretical models assumptions. The basic comprobation for verifying the system is to compare the measured data with the calculated data.

3.3.3.2 Expected outputs and standards.

The raw data from the acquistion system have to be included in a file with a .csv or .xlsx extension.

Despite there is a general norm (EN IEC 61757-1-1:2020-12) that includes FOS technology, there are no specific guidelines regarding the data storage and management

3.3.3.3 Evaluation of methods for data preprocessing and correction

3.3.3.3.1 Preprocessing

There are no preprocessing steps needed for the FOS data after their acquisition.

3.3.3.3.2 Data correction

Not applicable data because of the FOS data format.

3.3.4 Ground Penetrating Radar (GPR)

3.3.4.1 Evaluation of parameters for quality control

The evaluation for quality control of the GPR is done by comparing GPR data with cores. The reference coring should be made at 2-3 km intervals with a minimum 1/10 km road section.

There are some parameters which have to be checked to perform the quality control for GPR, such as:

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - Frequency of operation - Time between two transmitted pulses for which the reflected signals are recorded. - Sampling interval (time).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

	- Sampling interval (spatial). - Vehicle speed (if it is mounted on vehicle) - Resolution - Range of penetration - Acquisition type (continuous or not) - Dielectric properties of the propagation media
GPR 3D	- Distance between consecutive profiles

Table 3.6 – Parameters for quality control in GPR technique

3.3.4.2 Expected outputs and standards

The data from GPR is provided in a binary file format. Without a particular standard defined, there are some available formats depending on the manufacturer of the system such as:

- *.dt1, *.hd and *.gps for sensors and software.
- *.rd3, *.rd7, *..rad and *.cor for MALA geoscience.
- *.3dra and *.vol for radar systems.

3.3.4.3 Evaluation of methods for data preprocessing and correction

There are some operations to perform to the data to adapt to the format and characteristics required by the following steps, storage and analysis, in order to facilitate its management and avoid errors. Some part of data preprocessing and correction is common to both 2D and 3D systems, while another step differ between both GPR types.

3.3.4.3.1 Preprocessing

Preprocessing is done with the objective of adapt data to the required format that allows their ulterior storage and analysis. The data is provided by the GPR acquisition system an adequate format, a specific one depending on the manufacturer.

For the 3D surveys, 3D models and time slices are created by a specific GPR software.

3.3.4.3.2 Data correction

- **GPR data**

Correction	Description
Noise filtering	To eliminate noise.
Amplification	Amplificate the signal to compensate the mean (or median) attenuation observed in a GRP radargram.
Time-zero correction	Adhust all traces to common time-zero position (point which refers to first break of air wave of negative peak is notice).
Deconvolution	Contraction of signal wavelets to ”spikes” to enhance reflection event

Table 3.7 – Data correction in GPR technique

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.5 Guided Waves Propagation (GW)

3.3.5.1 Evaluation of parameters for quality control

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day
GW Propagation	- Amplitude of waves - Models - Frequency - Noise - Channels - Output voltage - Package characteristics (delay, package modulation, etc.) - Number of points. - Area dimensions.

Table 3.8 – Parameters for quality control in GW technique

For the validation, there are used numerical methods that studies the relationship between arrival time, amplitude of waves and the models used for fitting with the experimental data. Usually, it is also performed a simulation by numerical methods, as Finite Element Method and, for evaluate discontinuities from the measured data, is used the global matrix approach.

3.3.5.2 Expected outputs and standards.

There are some standards that regulate guide wave tests that automate the collection of the data generated in these tests. These standards are ISO 18211:2016 (*"Non-destructive testing – Long-range inspection of aboveground pipelines using guided wave testing with axial propagation"*), BS 9690-1:2011 and BS9690-2:2011 ("*Non destructive testing. Guide wave testing"*).

The information managed by guided wawe propagation test include:

- Graphic.
- Screen.
- File.
- Database.

There are no defined formats for data.

3.3.5.3 Evaluation of methods for data preprocessing and correction

3.3.5.3.1 Preprocessing

Not applicable.

3.3.5.3.2 Data correction

Not applicable.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.6 Light or Laser Imaging Detection And Ranging (LIDAR)

3.3.6.1 Evaluation of parameters for quality control

Quality control shall verify that each type of data obtained with the sensors complies with the required specification. The following are some of the parameters to be taken into account during pre-processing for quality control of the captured data.

These parameters to be checked in the quality control are related to various subsystems or sensors. Prior to performing the checking, it must be verified that the files obtained have the appropriate format, nomenclature and structure for the data type.

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day
Positioning system	- Geodetic reference system - Altitude and coordinates format - Cartographic projection - UTM zone - Trajectory resolution - Reference stations
Lidar	- Transverse field of view - Scanning frequency - Pulse frequency - Spatial resolution. Average density - Sensor calibration - Multiple intensity radiometric resolution - Maximum number of returns per pulse - Photogrammetric window - Vehicle speed at the time of data capture - Scanning height - Transverse overlay - Deviations from the vertical of the sensor - Covered area - Noise - Gaps
Imagery	- Transverse field of view - Sensor calibration - Automatic exposure control - Sensor spectral resolution - Radiometric resolution - Photogrammetric window - Pixel size and flying height - Longitudinal overlay - Transverse overlay - Camera vertical deviation - Verticality differences between consecutive frames - Changes of course between consecutive frames - Area to be overlaid - Orientation (direction of images)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	- Noise - Burned areas

Table 3.9 – Parameters for quality control in LIDAR technologies

3.3.6.2 Expected outputs and standards

The expected outputs for LiDAR will be different depending of the nature of the system (TLS or MLS).

Point cloud will be provided in a file with a standardised format. The file extension will be .las or .laz. The LAS standard support ten different PDRFs (Point Data Record Formats) with manage the point data in a different way.

Taking this into account, the structure of the point cloud data will be the following:

- Coordinates of the points expressed in a reference axis. Location in the space of the measurement point.
- Intensity data. Reflectivity of the measured point.
- Number of recorded pulse returns and/or waveforms. Energy intensity belongs to a single beam returned to the sensor over time. Pulse returns are the maximums of this curve energy intensity over time.
- LiDAR ID of the one that measure the point.
- Scanning angle. Position registered by the decoder when the measurement was made.
- Timestamp. Time when the measurement was made.

3.3.6.3 Evaluation of methods for data pre-processing and correction

Before any useful information for analysis can be obtained from the raw data captured by the sensors, a series of processes must be carried out. In this section these will be divided into two parts: pre-processing and correction.

3.3.6.3.1 Preprocessing

Preprocessing is the conversion of raw sensor data into standard formats. This process already combines information from different sources, e.g., by giving coordinates to each point or image using calibration data and trajectory records. The geolocation of the obtained data is the basis of the pre-processing and allows, for example, combining the image data with the point cloud data to obtain a coloured point cloud.

Preprocessing is different for TLS and MLS systems due to the different elements of which they are composed. While for the TLS, data from LiDAR is enough, for the MLS is needed to process data provided by IMU and the GNSS to obtain the necessary information about the trajectories followed by the MLS.

Consequently, trajectories and point cloud have to be processed in the right way.

- **Trajectories**

Trajectory data given by inertial measurement units (IMU) from satellite and inertial sensor observations are often collected in a binary format specific to the equipment used and cannot be immediately interpreted or converted to waypoints. This is because these files do not contain the points of these trajectories already processed, but a set of logs with observations and ephemerides from the satellites, detections from the inertial sensors, sensor status report,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

accuracy of the solution at each moment, etc., so that an external system can later reconstruct the trajectory accurately based on this information.

To obtain the trajectory, information not known to the sensor at the time of collection shall be used, such as GNSS information from a fixed base antenna or information from a nearby geodetic station available online, which will provide deviations in the satellite observations at the time of capture. Usually the files obtained will be in RINEX format, otherwise they may need to be converted before proceeding with the trajectory acquisition.

The pre-processing of the trajectory will normally be done in the software offered by the manufacturer of the IMU employed, although it might be possible to use other software that accepts the formats or logs collected by the equipment. In the software, a new project will be created with the data generated by the IMU during the acquisition and the information of the bases used in RINEX format (either own bases placed during the acquisition or permanent stations). Then, the required calibration data (distance and angular offsets between antenna, IMU, vehicle, DMI...) must be indicated to the program, with the precision with which they have been measured.

After this, a trajectory file with waypoints will be obtained in the desired format from those offered by the software used. These can be binary files with a known structure and therefore recognisable by other programs (such as Applanix SBET), ASCII files with header and tabulated trajectory data or KML files widely recognisable by GIS software, among others. Depending on the type of output file chosen, the software may vary the units of some of the data (for example, giving sexagesimal angles or radians), which must be taken into account during the design of the procedure.

- **Point clouds**

The point clouds obtained will vary in format depending on the sensor used but will generally consist of binary files with a different structure for each manufacturer. The manufacturers of each sensor provide the tools (software or API) and documentation necessary to generate a static point cloud around a single point (the centre of the lidar sensor).

To obtain a point cloud with each point georeferenced and in a standardised format, we must therefore have the trajectory already pre-processed in a single file in the chosen format. In addition, since the position and orientation of the lidar will vary with respect to the position and orientation of the vehicle or IMU (whichever has been used as a reference to generate the trajectory), it will also be necessary to have these lidar calibration data, which will consist on distance and angular offsets.

With this information it is possible to generate a point cloud taking into account the position of the lidar at the time of acquisition of each point. Since lidar sensors sample points in space at a much higher rate than the sampling rate of an IMU, it is necessary to interpolate the points in the trajectory, so the capture rate will define the accuracy of the cloud obtained in this step.

To make the point cloud more clear and facilitate later analysis of it, it exists the option to apply an algorithm of colourisation to the point cloud. With such an algorithm, each point of the cloud receives the RGB value of the raster pixel with the same location.

The generated cloud will preferably be generated in a standardised point cloud format such as LAS format, which can be opened by any point cloud reading or processing software or library.

- **RGB Images**

The images captured by the RGB sensors are saved in the chosen image format, either a standardised format such as PNG or JPEG or a raw format convertible by software offered by the manufacturer. In the case of RGB images taken by a 360° panoramic imaging camera, the output files will generally be produced in a proprietary format containing each file several

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

images. Using the software or API given by the manufacturer it is possible to obtain both the panoramic images or an individual image for each camera, as desired.

Although RGB cameras store in the metadata of the images obtained a timestamp for each image, this timestamp is generally not sufficiently accurate or the sensor time may not be correctly synchronised with the other equipment. It is therefore advisable to have a record of the number of images captured during the scan. If the triggers have been taken from a control system or from the IMU, there will be a file with both the triggers taken and the strobes received (a signal from the camera indicating the time at which the image was captured). In the case that it is the camera itself that performs the triggers by time, only the strobes record will be available. In any case, the strobes file will be the only one necessary, as it will contain a precise timestamp of the acquisition of each image, sorted by acquisition time.

Some cameras have input for NMEA and PPS signals, so that the produced images already contain a GPS position either in the image metadata or in an additional XML file with the position of each image. However, since this position is based exclusively on GNSS information collected by an antenna, it is preferable to calculate the position of each image from its timestamp, crossing the data with the trajectory data and taking into account the offsets of the camera with the vehicle or IMU. Some cameras can calculate their orientation from a stabilisation system, in which case this orientation data can be also used for the calibration.

Once the timestamp, position and orientation of each image has been obtained, it is possible to modify the metadata of these images to record the calculated values, although it is always advisable to generate an XML file with the names or paths of the images and this data.

RGB cameras can present images deformed due to the lens distorsion. This issue can be solved during the preprocessing phase by an adequate algorithm. For that, camera parameters are computed and used to calculate distortion coefficients. With the distortion coefficient, it is possible to remove the distortion from the image.

3.3.6.3.2 Data correction

Data correction consists of operations performed on the data that are mandatory when you want to process and analyse the data efficiently. For example, in order to have sufficient contrast in an image, the intensity histogram may have to be normalised to a greater or lesser extent, noise may have to be removed, and so on.

In other cases, correction is done not because of a lack of data quality, but because the data is too heavy, too dense or too precise for the type of processing to be done or even for sending and storing. In these cases, it is necessary to perform operations that reduce the density of these data, remove superfluous information, split them or compress them using more efficient formats.

- Trajectories

It is not necessary to correct the data.

- Point clouds

Correction	Description
Decimated	Reduction of the number of total points in a point cloud by eliminating those considered most superfluous following a chosen algorithm. In some more complex decimation algorithms, triangulated ways of replacing several points with a single point are calculated so that the structures do not significantly change their geometry.
Noise filtering	Elimination of points from the point cloud that fall below the established

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

	accuracy parameters, considered as "noise". There are several filters that perform the selection of these points. These filters can be based, among other criteria, on: - Detection of isolated or atypical points whose source can be a reflection or a false return - Elimination of returns with a very low reflectivity. - Points at such a distance that the errors due to angular uncertainty become very large..
Normalisation	The aim of normalising a point cloud is to obtain a model of the terrain only. Therefore, normalisation algorithms work by elaborating a digital terrain model (DTM), which draws the real terrain curve, and eliminating those points that do not lie on it or even interpolating those that are close to it to correct them.

Table 3.10 – Data correction in LIDAR point clouds

- **RGB Images**

Correction	Description
Histogram normalisation	Enhances the contrast of an image by normalising the histogram. For this, for each component of the RGB spectrum, the smallest value is shifted to 0 (black) and the largest to 255 (maximum), resulting in sharper differences between the colours in the image.
Histogram linearisation	Enhances contrast in images with dark areas usually due to backlighting. This is done by giving each intensity value the same probability of existing in the image, resulting in that the same number of pixels with each value exist. This effect can solve different problems than normalisation, but is more likely to generate false colours.
Radiometric corrections	Radiometric correction algorithms look for defects or artefacts in the images due to poor sensor calibration or particular atmospheric conditions. They are detected by studying patterns of pixels with a marked geometry and that contrast too much with the rest of the adjacent pixels, studying the image by bands. Depending on the radiometric correction method used or the size of the error found, some of these defects can be corrected by interpolation of neighbouring pixels.
Convolution filters	Some convolution filters are used to correct the sharpness of an image or to highlight its edges. They work like a mask transforming each pixel locally using information from its neighbouring pixels.
Low pass or interpolation filters	Low pass filters analyse images in the frequency domain, allowing only low frequencies. In this way, the image undergoes a process analogous to dilation by subtracting only those elements that occupy a larger surface area in the image. This could remove noise or grain from images.

Table 3.11 – Data correction in RGB images

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

3.3.7 Magnetic and Electrical Methods

3.3.7.1 Evaluation of parameters for quality control

The quality control and evaluation of the data should complies with the required by the specification using the following parameters:

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - Temperature - Calibration - Environmental conditions (explosive environment, etc.)
Electromagnetic Pulse Induction	- Location - Nominal diameter of the rebars - Distance between rebars - Distance on the structure - Cover range
MMM system	- Range of the magnetic field measured
MFL system	- Range of the material thickness
PEC system	- Range of the magnetic field measured - Eddy current density

Table 3.12 – Parameters for quality control in MEM

3.3.7.2 Expected outputs and standards.

There are several standards that defines the different aspected related to the magnetic and electrical methods, including the following:

- BS 4408: pt. 1, Non-destructive methods of test for concrete-electromagnetic cover measuring devices", British Standards Institution, London.
- DIN 1045: Guideline Concrete, reinforced and prestressed concrete structures.
- GOST R 52081-2003: Nondestructive testing. Method of metal magnetic memory. The terms an definitions.
- GOST R 52005-2003: Nondestructive testing. Method of metal magnetic memory. General requirements.
- ST RWS 004-03: Nondestructive testing. Welded joints of equipment and constructions. Method of metal magnetic memory.
- ISO 24497-1:2020 Non-destructive testing — Metal magnetic memory — Part 1: Vocabulary and general requirements.

The information managed from these methods is shown on a screen and also can be stored in storage medium. Structured in a file with an adequate format.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.7.3 Evaluation of methods for data preprocessing and correction

3.3.7.3.1 Preprocessing

Preprocessing is performed to adapt the data to the format and conditions required by the storage and analysis phases.

3.3.7.3.2 Data correction

- **Magnetic Memory method data**

Correction	Description
Filtering	Remove possible interference signals and meaningless outliers points.
Wavelet denoise	Separate measurement signal from noise.
Median smooth filter	To ensure high fidelity of the amplitude of the signal and real time without producing new quantization parameters.

Table 3.13 – Data correction in Magnetic memory method

- **Pulsed Eddy Current method data**

Correction	Description
Finite Element Analysis	To evaluate system beahaviour.

Table 3.14 – Data correction in Pulsed Eddy current method

- **Profometers**

Correction	Description
Color application	Color marking of the ranges of measured values.
Filtering	Filter to eliminate external disturbances effects.
Measure	Measuring concrete covers.

Table 3.15 – Data correction in Profometers

3.3.8 Mechanical Test on Cored Samples

3.3.8.1 Evaluation of parameters for quality control

3.3.8.2 Evaluation of parameters for quality control

The following parameters lead to the validation and control of the quality for the mechanical tests on cored samples:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Sensor	Parameter
General (related to project)	- Data format, nomenclature and structure - Date - Time of day - Numerical analysis and simulations - Climatic influence - Transport situations

Table 3.16 – Parameters for quality control in Mechanical Test on Cored Samples

3.3.8.3 Expected outputs and standards.

Regarding the data collection, the requirements are defined in the standard EN12504-1:2000.

The type of information obtained by mechanical tests on core samples are numeric data, such as strength values in Newtons (concrete strength, load applied).

3.3.8.4 Evaluation of methods for data preprocessing and correction

Thenumeric data collected do not need to be adapted because is collected in a laboratory test by a machine or by the laboratory technician, depending on the type of test, directly with the required format and characteristics.

3.3.8.4.1 Preprocessing

Not applicable.

3.3.8.4.2 Data correction

Not applicable.

3.3.9 Micro Electro-Mechanical Systems (MEMS) - Accelerometers

3.3.9.1 Evaluation of parameters for quality control

There are some aspects to evaluate in terms of quality control, such as:

Sensor	Parameter
General	- Data format, nomenclature and structure - Date - Timestamp
Accelerometers	- Sampling frequency - Measure expression (LSB or as a measure of gravity) - Error - Noise - Cross-axis sensitivity

Table 3.17 – Parameter for quality control in Accelerometers technology

In addition to the above parameters, data can be considered valid if it is in the expected range of values for the specific application. Furthermore, to ensure the file received is not corrupted, it has to be verified that it has the expected structure, such as number of columns, file extension or type of information.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.9.2 Expected outputs and standards.

The Outputs expected for the accelerometers are the accelerations, so accelerometerers generate files based on numeric values. There are not standards defined for the management of the data provided by the accelerometers, but it is possible to define some formats to be used:

- Files with extension *.csv.
- MySQL Database files.
- PARQUET column-oriented data files.

Acquired data could have several fields. Nevertheless, it is possible to define some essential fields, that are:

- Name of the clinometer/accelerometer (considering they are usually part of a wider sensors network)
- Timestamp of acquired data
- Acquired data in each of the measuring axis (rotation, acceleration, etc.)

3.3.9.3 Evaluation of methods for data preprocessing and correction

3.3.9.3.1 Preprocessing

Preprocessing is the conversion of raw sensor data into standard formats. In this case, next techniques will be carry out:

- Calibration: conversion of the sensor direct measurement in acceleration.
- Filtering: low-pass filters are applied to remove noise and, more in general, the signal content on high frequencies (not of interest for civil applications). In some cases also high-pass filters can be applied: the aim is to keep only the dynamic information from the data, removing eventual static movements.
- Oversampling
- Decimation: application of digital filters to reduce the amount of data originally acquired; decimation should always take place after the application of any low-pass filters.

3.3.9.3.2 Data correction

Data correction is not applied because the data provided by the accelerometers are numeric values which not have any predefined operation that have to be done.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

3.3.10 Micro Electro-Mechanical Systems (MEMS) - Clinometers

3.3.10.1 Evaluation of parameters for quality control

Sensor	Parameter
General	- Data format, nomenclature and structure - Date - Time of day
Accelerometers	- Sampling frequency - Measure expression (degrees or as a measure of gravity) - Number of measuring axis - Sensitivity - Error

Table 3.18 – Parameters for quality control in Clinometers technology

In addition to the above parameters, data can be considered valid if it is in the expected range of values for the specific application. Furthermore, to ensure the file received is not corrupted, it has to be verified that it has the expected structure, such as number of columns, file extension or type of information.

3.3.10.2 Expected outputs and standards.

The Outputs expected for the clinometers are the accelerations, so accelerometerers generate files based on numeric values. There are not standards defined for the management of the data provided by the clinometers, but it is possible to define some formats to be used:

- Files with extension *.csv.
- MySQL Database files.
- PARQUET column-oriented data files.

Acquired data could have several fields. Nevertheless, it is possible to define some essential fields, that are:

- Name of the clinometer/accelerometer (considering they are usually part of a wider sensors network)
- Timestamp of acquired data
- Acquired data in each of the measuring axis (rotation, acceleration, etc.)

3.3.10.3 Evaluation of methods for data preprocessing and correction

3.3.10.3.1 Preprocessing

Preprocessing is the conversion of raw sensor data into standard formats. In this case, next techniques will be carry out:

- Calibration: conversion of the sensor direct measurement in an angle measure
- Removal of the zero reading and, as consequence, of errors in sensors initial positioning

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- Removal of environmental influences on data (temperature, humidity, etc.). Data correction from environmental influences is usually done with linear (or non-linear) regression techniques.
- Data resampling: considering clinometers measure structures static behaviour, usually data downsampling is applied.
- Moving average: used to remove data variability, allows to highlight data trend on medium/long period.

3.3.10.3.2 Data correction

Not applicable because the outputs from the clinometers are numeric values which not have any predefined correction to be done.

3.3.11 Optical and Visual Testing. Boroscopy and endoscopy

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - Operating temperature - Working length of the probe
Images	- Viewing angle - Field of view - Sensor calibration - Automatic exposure control[ooooo] - Pixel size - Noise

Table 3.19 – Parameters for quality control in boroscopy and endoscopy

3.3.11.1 Evaluation of parameters for quality control

In terms of ensuring that the files is not corrupted, there should not be any issues with the files if the pictures and videos are correctly stored on the SD card.

3.3.11.2 Expected outputs and standards

The existing standard for the endoscopes and boroscopes is EN 13018:2016.

The information generated in this methods are images and the expected format for them is *jpg.

3.3.11.3 Evaluation of methods for data preprocessing and correction

3.3.11.3.1 Preprocessing

In the preprocessing, the raw data have to be adapted to the standard required format and characteristics. In the case of the boroscope and endoscope, the images captured by the cameras are saved in the chosen image format, in this case a standardized format (JPEG).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

3.3.11.3.2 Data correction

Correction	Description
Histogram normalisation	Enhances the contrast of an image by normalising the histogram. For each channel of the image, the smallest value is shifted to 0 (black) and the largest to 255 (maximum), resulting in sharper differences between the colours in the image.
Histogram linearisation	Enhances contrast in images with dark areas usually due to backlighting. This is done by giving each intensity value the same probability of existing in the image, resulting in that the same number of pixels with each value exist. This effect can solve different problems than normalisation, but is more likely to generate false colours.
Radiometric corrections	Radiometric correction algorithms look for defects or artefacts in the images due to poor sensor calibration. They are detected by studying patterns of pixels with a marked geometry and that contrast too much with the rest of the adjacent pixels, studying the image by bands. Depending on the radiometric correction method used or the size of the error found, some of these defects can be corrected by interpolation of neighbouring pixels.
Convolution filters	Some convolution filters are used to correct the sharpness of an image or to highlight its edges. They work like a mask transforming each pixel locally using information from its neighbouring pixels.
Low pass or interpolation filters	Low pass filters analyse images in the frequency domain, allowing only low frequencies. In this way, the image undergoes a process analogous to dilation by subtracting only those elements that occupy a larger surface area in the image. This could remove noise or grain from images.

Table 3.20 – Data correction in boroscopy and endoscopy

3.3.12 Qualitative Chemical Methods

3.3.12.1 Evaluation of parameters for quality control

In terms of quality control, there are some parameters to check:

Sensor	- Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - pH indicators - Inspected area - Voltage range

Table 3.21 – Parameters for quality control in qualitative chemichal methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.12.2 Expected outputs and standards.

There are standards that defines different conditions about the qualitative chemichal methods but not about the data collection.

The data managed in this technique fits into the following data types:

- Files.
- Graphical.
- Images.

The formats used for managed this information are:

- .txt
- .pdf
- .xlsx

3.3.12.3 Evaluation of methods for data preprocessing and correction

Qualitative chemical methods are carried out in a laboratory and data collection is performed manually by laboratory technicians. Therefore, the data do not require preprocessing or correction.

3.3.12.3.1 Preprocessing

Not applicable.

3.3.12.3.2 Data correction

Not applicable.

3.3.13 Quantitative Chemical Methods

3.3.13.1 Evaluation of parameters for quality control

There are some parameters to check to perform the quality control of the technique as:

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - pH - Ambient conditions - No magnetic fields

Table 3.22 – Parameters for quality control in quantitative chemichal methods

3.3.13.2 Expected outputs and standards.

There are standards that defines different conditions about the qualitative chemichal methods but not about the data collection.

The data managed in this technique fits into the following data types:

- Numeric.
- Graphical.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- IR images.

To manage this information are used the following file formats:

- .txt
- .xlsx

3.3.13.3 Evaluation of methods for data preprocessing and correction

Quantitative chemical methods are carried out in a laboratory and data collection is performed manually by laboratory technicians. Therefore, the data do not require preprocessing or correction.

3.3.13.3.1 Preprocessing

Not applicable.

3.3.13.3.2 Data correction

Not applicable.

3.3.14 Radiological and nuclear methods

3.3.14.1 Evaluation of parameters for quality control

It has to be verified during through the quality control that data complies with the required specification in terms of data type and structure. For this purpose, some parameters should be checked:

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day - Exposure time - Irradiation exposure time - Direction and method of exposure
Computed X-ray/Gamma Tomography	- Resolution
Neutron Radiography	- Channels - Greyscale resolution - Image sharpness
Nuclear Magnetic Resonance Spectroscopy	- Frequency - Wavelength - Calibration - Sample preparation - Magnetic field

Table 3.23 – Parameters for quality control in Radiological and nuclear methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

3.3.14.2 Expected outputs and standards

There are different options for applying radiological and nuclear methods but there are some common points about the expected outputs they provide. Therefore, the data to manage and store will have some general characteristics. The data can be numeric and graphic. The data has to be structured as a file which can be stored in some storage medium. Other possibility is to store it in a database. In both cases, it has to be used an adequate file format. For thei images, the appropiate file extension is SER while for the numeric data it can be used files with FID format. There are standards that describe the way of performing the methods, but not for the data management.

3.3.14.3 Evaluation of methods for data preprocessing and correction

3.3.14.3.1 Preprocessing

The preprocessing aims in adapting the data to the required formats and standards. In the case of the data acquired by radiological and nuclear methods, it is necessary the performance of some preprocessing steps to make the data understandable and functional for the next stages, both analysis, processing and storage activities.

If it is used the Neutron Radiography method, the preprocessing should include the application of scattering correction and Monte Carlo computation method to ensure the validity of the acquired data.

3.3.14.3.2 Data correction

Data correction consists of operations performed on the data that are mandatory when you want to process and analyse the data efficiently. Those operation may differ depending on the method which it is used but can include but can include some common image operations.

- **Images**

Correction	Description
Noise filtering (domain)	Denoise image in the spatial domain.
Noise filtering (frequency)	Denoise image in the frequency domain.
Interpolation	The objective is to make equal the physical spacing for the input images.
Registration	Align interest area with a reference image.
Histogram Modification	Enhances the contrast of an image.
Normalization	Apply linear transformation to enforce smallest and large values to be mapped in a particular range (usually to 0-255 or 0-65535).
Standardization	To have comparable values between different values between NMR images.

Table 3.24 – Data correction in Radiological and nuclear methods

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.15 Remote sensing

3.3.15.1 Evaluation of parameters for quality control

Quality control shall verify that each type of data obtained with the sensors complies with the required specification. The following are some of the parameters and methods to be taken into account during pre-processing for quality control of the captured data.

The CAL-VAL process starts already before the launch of the platform, because it's the unique opportunity where can directly calibrate and characterize physically the satellite, After the launch continues this process directly to obtain Level 1 and 2 data reliable and calibrate. The CAL-VAL of one mission includes the sensor calibration, verify the algorithm, the geophysical data validation and the intercomparison with other missions, all of this going to the uncertainties quantification. This process can be better through the comparison of multiple independent sources so that confidence is generated in the veracity of the data.

Another comprobation to be done is that the file received is not corrupted. There are two aspects to check:

- A GIS software is able to read the file correctly.
- Visual validation. The image is understable by humans.

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day
Radar satellite images	- Location - Size - Shape - Color - Height - Depth - Overlay - Wavelength - Incidence angle - Covered area - Orbital elevation
Optical satellite images	- Atmosphere conditions - Spatial resolution - Field of view - Calibration - Resolution - Pixel size - Overlay - Camera vertical deviation - Verticality differences between consecutive frames - Changes of course between consecutive frames - Orientation (direction of images) - Noise - Orbital elevation

Table 3.25 – Parameters for quality control in Remote sensing technique

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.15.2 Expected outputs and standards

There are a great variety of satellites with different uses and technologies so there are many different possible file formats for their outputs. However, in this document it will be defined a required format to make satellites data available.

Furthermore, images will be different depending the type of the sensor used (active or passive). In the case of the active sensors, they will generate radar satellites images, usually with a high resolution, while the passive sensors acquire optical images.

For this technique will be user COSAR files as a standard. COSAR files could serve as a container hosting complex for the sensor data.

A COSAR file is formed by the following informaiton:

- Annotation files for the schema definitions in this document (".xml").
- Images, with types TIFF or GeoTIFF, with different depths and representations (".tif")
- ".cos" for the COSAR image format specified here in.
- Binary raster file (".bin")
- Standard PNG (".png").
- Text files (".txt").

3.3.15.3 Evaluation of methods for data pre-processing and correction

Before any useful information for analysis can be obtained from the raw data captured by the sensors, a series of processes must be carried out. In this section these will be divided into two parts: pre-processing and correction.

3.3.15.3.1 Preprocessing

In the preprocessing step, the raw data have to be adapted to the standard required format and characteristics.

The satellite acquires several images at different times and perspectives. Due to the fact that an ortographic image is created with the information from that acquired images, some preprepocessing steps have to be applied to make these data understable for processing steps.

Orbit state vectors have to be applied to provide an accurate satellite position and speed information. For being more precise, these orbit state vectors are determined after several days.

To mosaic multiples images provoke some issues. The images that will compose the result image, have to be standardized (size, illumination conditions, etc) before their combination. The illumination must be uniform between different frames. However, due to different conditions, as in example, the atmosphere, it could appear some scattering of radiation that will affect to the surface illumination.

It have to be taken into account the pixel overlapping that occurs when the same pixel is viewed in different frames, so in the final image every pixel has to be represented only once.

A preprocessing process is to do a geometric registration of the images. It can be applied to one single image if there are also information about the geographic coordinates. In this case, it is based in identifying the image coordinates of ground control points (some identificable points) and matching them into ground coordinates. This is called an image-to-map registration. Once the different ground control points have been identified, the coordinate information is processed to determine the transformation required to be applied to the original

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

image coordinates to map them into the new ground coordinates. This process could be also done by registering some images into another image, called image-to-image registration.

3.3.15.3.2 Data correction

- For both radar and optical images:

Correction	Description
Border noise removal	Remove low intensity noise and invalid data on scene edges.
Thermal noise removal	Reduce noise effects
Calibration	Converting digital pixel values to radiometrically calibrated SAR backscatter.
Speckle filtering	Reduce speckle.
Range Doppler terrain correction	Correct geometry distorsion using a digital elevation model to correct the location of each pixel.
Conversion to dB	Convert the unitless backscatter coefficient to dB by using a logarithmic transformation.
Histogram normalisation	Enhances the contrast of an image by normalising the histogram. For this, for each component of the RGB spectrum, the smallest value is shifted to 0 (black) and the largest to 255 (maximum), resulting in sharper differences between the colours in the image.
Histogram linearisation	Enhances contrast in images with dark areas usually due to backlighting. This is done by giving each intensity value the same probability of existing in the image, resulting in that the same number of pixels with each value exist. This effect can solve different problems than normalisation, but is more likely to generate false colours.
Radiometric corrections	Radiometric correction algorithms look for defects or artefacts in the images due to poor sensor calibration or particular atmospheric conditions. They are detected by studying patterns of pixels with a marked geometry and that contrast too much with the rest of the adjacent pixels, studying the image by bands. Depending on the radiometric correction method used or the size of the error found, some of these defects can be corrected by interpolation of neighbouring pixels.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Convolution filters	Some convolution filters are used to correct the sharpness of an image or to highlight its edges. They work like a mask transforming each pixel locally using information from its neighbouring pixels.
Low pass or interpolation filters	Low pass filters analyse images in the frequency domain, allowing only low frequencies. In this way, the image undergoes a process analogous to dilation by subtracting only those elements that occupy a larger surface area in the image. This could remove noise or grain from images.

Table 3.26 – Data correction in Remote sensing technique

3.3.16 Surface Measurement

3.3.16.1 Evaluation of parameters for quality control

The quality control involves parameters such as:

Sensor	Parameter
General (related to project or various sensors)	- Data format, nomenclature and structure - Date - Time of day
Rebound test	- Hammer type - Concrete type
Penetration test	- Windsor system type - Probe material - Power setting - Hardness of the aggregate - Spacing between probes
Pull-out test	- Type of load - Axis of the anchor

Table 3.27 – Parameters for quality control in Surface measurement

3.3.16.2 Expected outputs and standards.

The standards used for surface measurements are ISO/DIS 8046, ASTM C900-94 and ASTM C803-82, but these standards refers to the way of perform the tests and not about the data management.

The information managed from surface measurements will be files with the numeric values relative to the measurements. The formats to use will be:

- *.txt.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- *.xlsx.

3.3.16.3 Evaluation of methods for data preprocessing and correction

The information to storage is numeric data which no needs specific preprocessing or correction for this purpose because of the nature of the technique and the data collection needed for it.

3.3.16.3.1 Preprocessing

Not applicable.

3.3.16.3.2 Data correction

Not applicable.

3.3.17 Water Penetration Test / Permeability Test

3.3.17.1 Evaluation of parameters for quality control

The quality control involves the use of the following parameters:

Sensor	Parameter
Water resistance / absorption test	- Data format, nomenclature and structure - Date - Sample identification - Direction of the water supply in relation to the sample formation (perpendicular or in parallel - Number of samples - Depth of the water penetration - Area of application - Temperature

Table 3.28 – Parameters for quality control in Water Penetration Test / Permeability Test

3.3.17.2 Expected outputs and standards.

The standard for the water penetration test is EN 12390-8:2019. However, it specifies the conditions and ways to perform the test but not the data structure.

The data collected by this technique is numeric, so if it is needed to storage them, an adequate file has to be used.

3.3.17.3 Evaluation of methods for data preprocessing and correction

The data from the water penetration test is collected and managed manually by laboratory technician, so there are no needs in terms of data preprocessing and correction.

3.3.17.3.1 Preprocessing

Not applicable.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.17.3.2 Data correction

Not applicable.

3.3.18 Water Resistance / Absortion Test

3.3.18.1 Evaluation of parameters for quality control

For the quality control, the following parameters have to be taken into account:

Sensor	Parameter
Water resistance / absorption test	- Data format, nomenclature and structure - Date - Time of day - Material (concrete, stone, cement-lime) - Samples dimensions - Temperature - Mass change - Water absorption rate

Table 3.29 – Parameters for quality control in Water Resistance / Absortion Test

3.3.18.2 Expected outputs and standards.

The standards for this technique are not about data formats but are for define the conditions for performing the technique.

The information generated by water resistance/absorption test is numeric, so it could be managed by a file consequent to this data type.

3.3.18.3 Evaluation of methods for data preprocessing and correction

The water resistance test have to be performed in a laboratory and the reporting is done manually by laboratory technicians, so there are no needs in terms of data preprocessing and correction.

3.3.18.3.1 Preprocessing

Not applicable.

3.3.18.3.2 Data correction

Not applicable.

3.3.19 Weight in Motion Systems (WIM-Systems)

3.3.19.1 Evaluation of parameters for quality control

There are the following parameters in terms of quality control:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

Sensor	Parameter
WIM	- System manufacturer - Period of test - Date and time - Test conditions - Location - Lane number - Number of test vehicles - Vehicle types - Speed [km/h] - Gross weight - Axle loads by axle rank or group of axle loads measured in motion - Static references values of weights and loads.

Table 3.30 – Parameters for quality control in WIM-Systems

The validation of the measurements along with the processing of post-survey data (including the attachment of a digital signature) is performed by CPU-control devices.

There are specific protocols inside the platform software responsible for generation of the proper file to ensure the file is not corrupted.

3.3.19.2 Expected outputs and standards.

Traffic management solutions in general and, particularly, WIM systems are not standardized. Despite WIM systems main document is COST 323, there are no uniformity and standards with respect to the data management of these systems.

The expected outputs include:

- Images.
- Files.
- Database.
- Storage medium.

To store this information, it must be the following formats:

- .jpg for images.
- .pdf for the storage of the rest of the data.

3.3.19.3 Evaluation of methods for data preprocessing and correction

3.3.19.3.1 Preprocessing

- **Images**

The images captured have to be in the chosen image format, in this case a standardised format such as JPEG or a raw format convertible by software offered by the manufacturer.

- **Pdf**

No particular preprocessing needed for this type of data.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

3.3.19.3.2 Data correction

- **Images**

Correction	Description
Border noise removal	Remove low intensity noise and invalid data on scene edges.
Thermal noise removal	Reduce noise effects
Calibration	Converting digital pixel values to radiometrically calibrated SAR backscatter.
Histogram normalisation	Enhances the contrast of an image by normalising the histogram. For this, for each component of the RGB spectrum, the smallest value is shifted to 0 (black) and the largest to 255 (maximum), resulting in sharper differences between the colours in the image.
Histogram linearisation	Enhances contrast in images with dark areas usually due to backlighting. This is done by giving each intensity value the same probability of existing in the image, resulting in that the same number of pixels with each value exist. This effect can solve different problems than normalisation, but is more likely to generate false colours.
Radiometric corrections	Radiometric correction algorithms look for defects or artefacts in the images due to poor sensor calibration or particular atmospheric conditions. They are detected by studying patterns of pixels with a marked geometry and that contrast too much with the rest of the adjacent pixels, studying the image by bands. Depending on the radiometric correction method used or the size of the error found, some of these defects can be corrected by interpolation of neighbouring pixels.
Convolution filters	Some convolution filters are used to correct the sharpness of an image or to highlight its edges. They work like a mask transforming each pixel locally using information from its neighbouring pixels.
Low pass or interpolation filters	Low pass filters analyse images in the frequency domain, allowing only low frequencies. In this way, the image undergoes a process analogous to dilation by subtracting only those elements that occupy a larger surface area in the image. This could remove noise or grain from images.

Table 3.31 – Data correction in WIM-Systems

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

4. Data storage and management

This chapter describes the ongoing European initiatives on high-level architecture for digital platforms for the construction sector, followed by a proposal for conceptual data architecture for asset management, addressing inspection, monitoring and maintenance data of transport infrastructures.

4.1 EU developments of data platforms that are relevant for the construction sector

The 2021's Analytical Report of the European Construction Sector Observatory (ESCO) (Denmark, 2021) shortlisted the EU policy initiatives and framework put in place in relation to supporting the digitalisation of the EU construction sector, namely: 1. Digitalisation policies related to the construction sector; 2. Construction-related digital platforms; 3. Public procurement policies with a specific focus on fostering digitalisation; 4. Government e-services; 5. Digital building logbooks.

Digital platforms are thus among the important policy initiatives. Aligned with this, the DigiPLACE project (2019-2021) (CORDIS, 2019) (DigiPLACE, 2021) has taken place with the aim to create a Reference Architecture Framework (RAF) for the digital industrial platform for the construction sector based on a shared consensus along the entire value chain and supported by a strategic roadmap. The RAF is a comprehensive set of common guidelines for building and deploying interoperable digital platforms for the construction sector across Europe. The DigiPLACE RAF is schematically presented as follows:

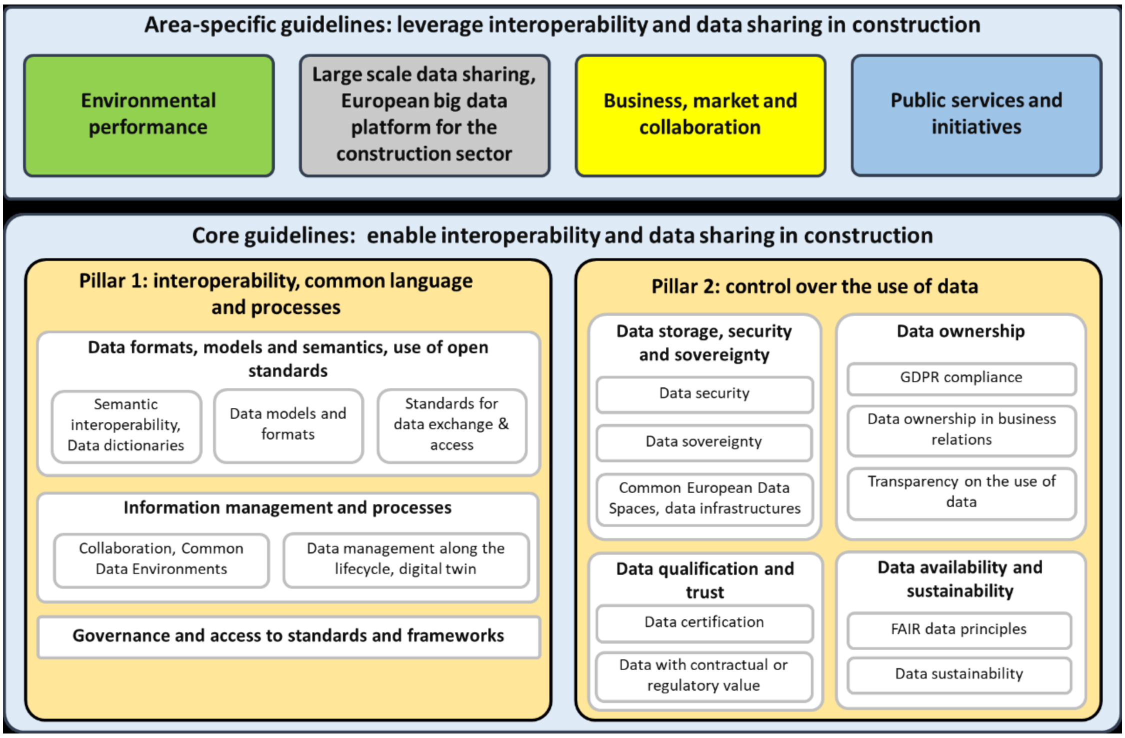

Figure 4.1 – DigiPLACE Reference Architecture Framework (RAF)

On data sharing, DigiPLACE RAF aims to link with the ongoing initiatives on European data strategy (EUComission, 2018), especially the Common European data spaces (EU Comission, 2021).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

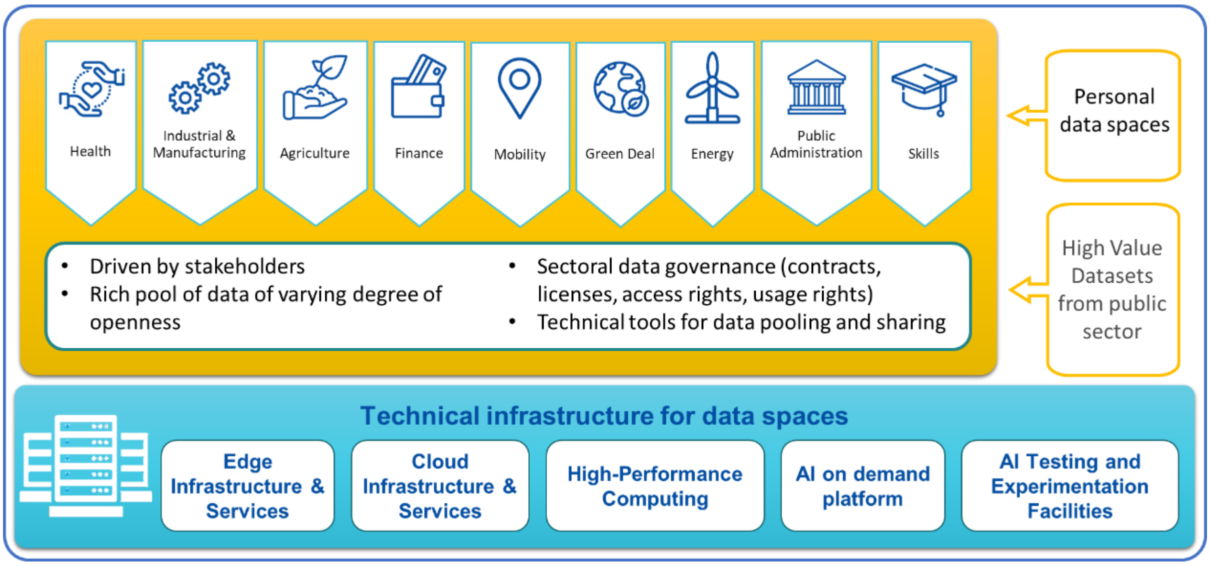

Figure 4.2 – Common European data spaces

At the EU level, there is an ongoing initiative for a cloud-based data infrastructure, known as GAIA-X (Gaia-x, 2022). Gaia-X is a European project bringing people from different companies, research institutions, associations, administrations, and politics together to work towards a common goal. Together, they build on the widest spectrum of expertise to co-create the future of the digital infrastructure for Europe - across dedicated data spaces serving the most critical industries. The organisational structure of Gaia-X is built on three pillars: the Gaia-X Association, the national Gaia-X Hubs, and the Gaia-X Community. Within these, there are various working groups and committees. The exchange within, between and beyond these pillars towards other stakeholders (e.g. EU Commission, international initiatives) is ensured.

GAIA-X is a federated and secure data infrastructure. The architecture of Gaia-X is based on the principle of decentralisation. Gaia-X is the result of a multitude of individual platforms that all follow a common standard – the Gaia-X standard. Together, we are developing a data infrastructure based on the values of openness, transparency, and trust. So, what emerges is not a cloud, but a networked system that links many cloud services providers together.

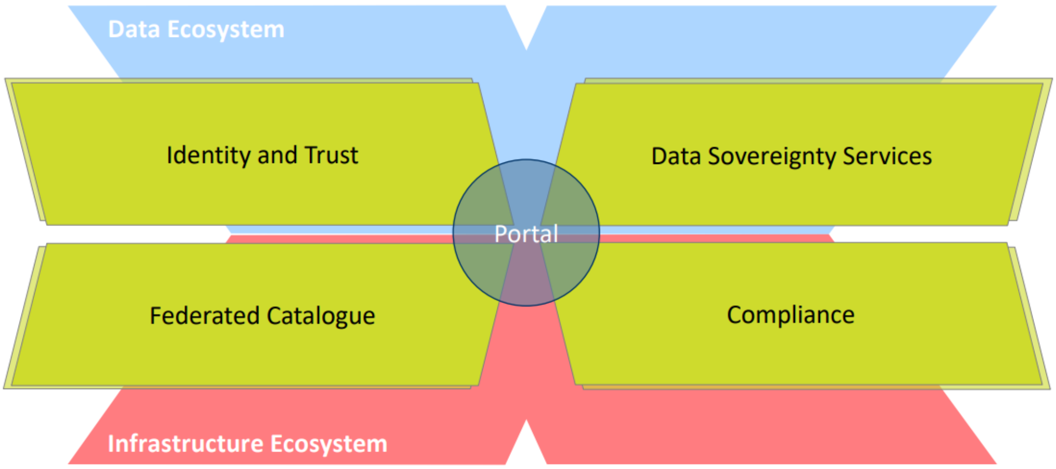

Figure 4.3 – Gaia-X Federation Services and Portal as covered in the Architecture Document (Gaia-x, 2022).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

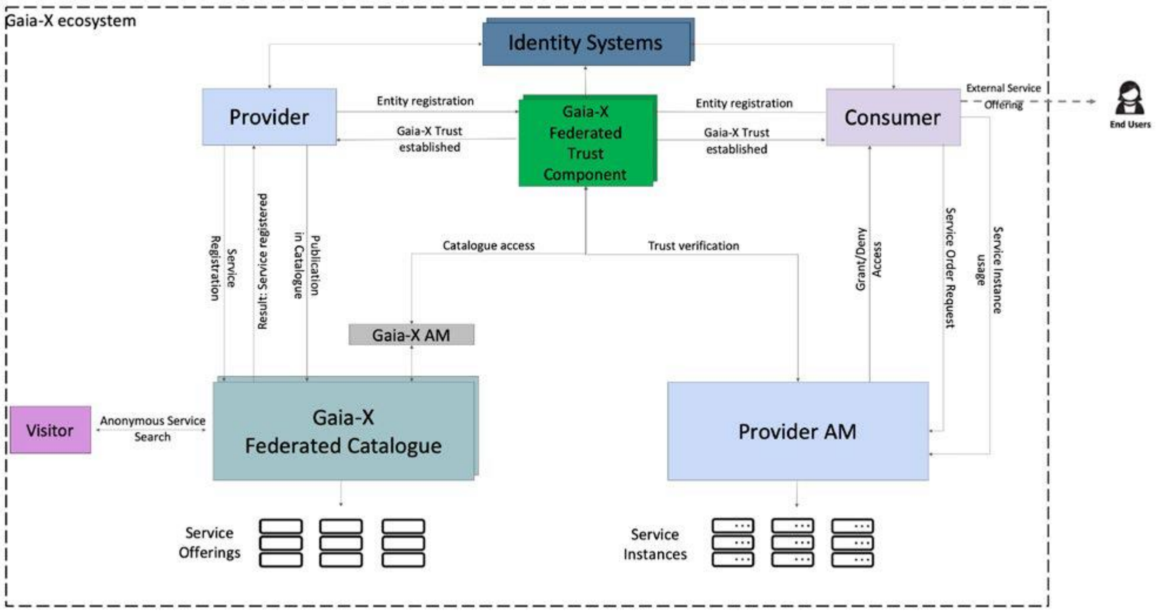

Figure 4.4 – Detailed Level Design of the Gaia-X Federated Trust Model (Gaia-x, 2022).

An example of the added values of GAIA-X for smart management of transport infrastructures is presented by GAIA-X Hub Germany (Buziek & Mundt, 2022):

> *Road construction planning needs to take into account a large number of interests. Therefore, it is necessary to involve various authorities and stakeholders, including property owners, road construction authorities, transport ministries, land surveying offices, environmental protection agencies, and other interested parties such as property developers, energy suppliers, and the general public.*
>
> *At present, due to limited possibilities for authorities to cooperate in a common IT environment, the various stakeholders are engaged successively. For one thing, there are different restrictions in place regarding the purpose and use of data, as well as questions of competence. For another, amalgamating the relevant data is often impossible due to the prevalence of isolated approaches (as regards technology or competence) or because there are no procedures available to provide data for mutual use within a reasonable time frame. Currently, there is no uniform platform for collaboration and the secure provision of data with all the necessary functionalities and rights to access and use data. That is why current utilisation processes are mostly limited to simple data provision, leaving the vast potential of real-time cooperation untapped, including advantages in terms of flexible and purposeful data use. Moreover, objections on the part of communities and associations often go unheeded during the planning phase, thereby stalling the process. Risks tend to arise regarding the quality of plans and the traceability of modifications, which leads to additional project costs for the planners.*
>
> *What added value does the "GAIA-X project" offer?*
>
> - *GAIA-X enables the integration of additional existing IT solutions or data bases. Infrastructure projects, for example, could thus benefit from intermodal linkages to mapping data from environmental or species protection activities. Moreover, it is possible to collect, process, and network data in a continuous manner.*
> - *GAIA-X helps to ensure permanent accessibility to the cloud-based data space while guaranteeing information security and data protection.*
> - *Apart from speeding up procedures, GAIA-X allows to ensure the consistency of spatial data such as those needed for Building Information Modelling (BIM) – ad-hoc*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

adaptations for different construction phases are thus no longer necessary. This, in turn, has a positive impact on assuring the quality of project planning, which is especially relevant for projects that are planned across competences or national borders.

- *A safe and trustworthy cloud can also allow SMEs lacking the required resources to participate in the geodata value chain.*

Another existing initiative at the EU level is the Industrial Data Spaces (IDS). IDS is a Reference Architecture model that aims to provide a common frame for designing and deploying Industry IoT infrastructures (i.e. sensor-enabled manufacturing equipment will allow real time communication, smart diagnosis and autonomous decision making). Such a Reference Architecture can be implemented based on FIWARE open source software components (Generic Enablers). FIWARE-based IDS implementation fits the requirements of the IDS Reference Architecture providing open source software suitable to any Industry 4.0 environment (Alonso, 2018).

FIWARE and IDS were both named by the European Union (EU) with regards to the progress of the Digitising European Industry (DEI) initiative. IDS addresses a key topic in the evolution of Industry 4.0: How can companies and institutions build a space where data is shared in a decentralized manner so that each organization can use available data to improve their processes, as well as govern and monetize data exported to third parties. The International Data Spaces Association (IDSA) is creating a reference architecture to implement secure and trustworthy data exchanges. Data providers hereby keep control over the usage of their data, also referred to as "data sovereignty" (International Data Spaces, s.f.).

FIWARE is an open source initiative defining a universal set of standards for context data management which facilitate the development of Smart Solutions for different domains such as Smart Cities, Smart Industry, Smart Agrifood, and Smart Energy. In any smart solution there is a need to gather and manage context information, processing that information and informing external actors, enabling them to actuate and therefore alter or enrich the current context. FIWARE is focused on industry reference architecture, which is compliant with the existing industry architectures, such as the Reference Architecture Model Industrie 4.0, the Industrial Data Space Reference Architecture or the Industrial Internet Consortium Reference Architecture. The schematic representation of FIWARE ecosystem can be found in the following figure.

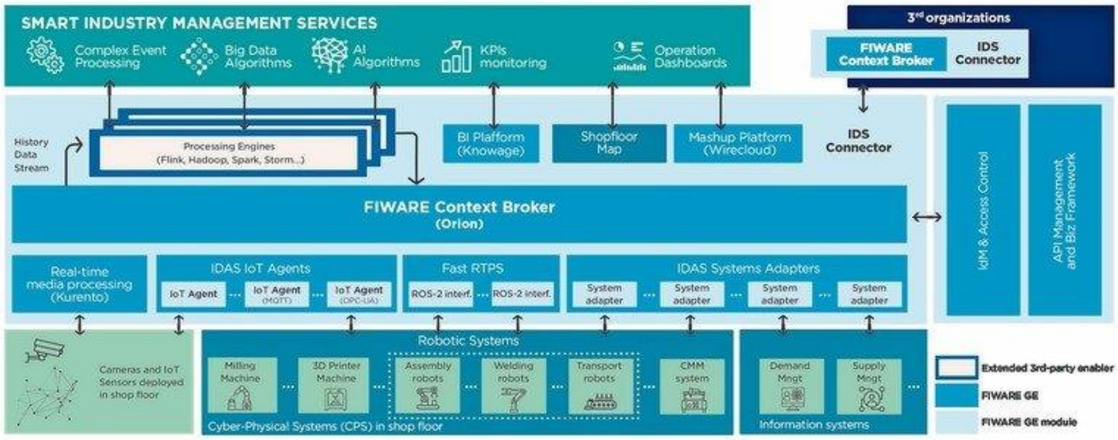

Figure 4.5 – Reference architecture for smart industry (Fiware, 2022).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

4.2 An approach for data integration in transport infrastructure asset management

With regards to data, transport infrastructure assets have several unique characteristics, among others:

- there is often a 'network level' on which the individual infrastructure assets are connected together and have their impact on usage;
- real-time updates and actions are not the first priority (with exception in case of emergency) as most construction-related measures are concerned with long-term planning;
- analyses of existing infrastructures typically address the full asset lifecycle covering the programming, design, build and operation phases;
- transport infrastructure assets have a different Level of Detail (LoD) compared to the infrastructure network at asset level; therefore, the intended data ecosystem should support both LoD, including the relations between these LoD.

Taking these characteristics into consideration, the purpose of a data integration architecture for transport infrastructure assets is as follows:

- On the level of individual assets or individual projects, data integration should support project-specific data collected from multiple sources, data processing and analysis focusing on project-specific objectives, and the use of specific digital tools for the project or a certain type of projects.
- On the level of a network of assets or a series of projects, the data ecosystem should support reuse of data, data analysis results and tools from other projects as well as generalization of information to obtain new global insights and knowledge.

In handling the data integration, the FAIR principles for data management should be applied. These FAIR (Findable, Accessible, Interoperable, Reusable) principles comprise (GoFair, 2022):

- To be Findable:
  - (meta)data are assigned a globally unique and eternally persistent identifier.
  - data are described with rich metadata.
  - (meta)data are registered or indexed in a searchable resource.
  - metadata specify the data identifier.
- To be Accessible:
  - (meta)data are retrievable by their identifier using a standardized communications protocol.
  - the protocol is open, free, and universally implementable.
  - the protocol allows for an authentication and authorization procedure, where necessary.
  - metadata are accessible, even when the data are no longer available.
- To be Interoperable:
  - (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.
  - (meta)data use vocabularies that follow FAIR principles.
  - I3. (meta)data include qualified references to other (meta)data.
- To be Re-usable:
  - meta(data) have a plurality of accurate and relevant attributes.
  - (meta)data are released with a clear and accessible data usage license.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

- (meta)data are associated with their provenance.
- (meta)data meet domain-relevant community standards.

There are several basic requirements for a generic data integration architecture for transport infrastructure, such as (TNO internal ERP program on data management):

- The data integration architecture should facilitate both data services and analysis that cover:
  - authentication/authorization;
  - documents and data storage (content, meta-data & data structure) and access (browsing or machine-based);
  - document/data modelling and linking (i.e. adding “semantics”);
  - meta-data assignment and version management);
  - data cleaning like corrections and alignment;
  - data transformation, translation and conversion;
  - data visualization;
  - backup/archiving
  - data processing;
  - expert computation.
- The data integration architecture should ensure an adequate level of performance in terms of capacity, reliability and long-term support concerning:
  - reasonable costs, including initial cost, licenses, usage-dependent fees;
  - range of choices of commercial-on-the-shelf (COTS) and open-source software (OSS);
  - interoperability to support W3C Linked Data / Semantic Web standards and Big Data open standards;
  - compliance to the relevant IT systems and software used by the asset managers and engineers;
  - flexibility to future adaptations and developments, such as the development of creation/capture, calculation/analysis, decision support, learning & control methods, combined Levels of Detail (LoD), and implementation of Artificial Intelligence (AI) / Machine Learning (ML);
  - alignment with future strategies regarding Common Data Environment (CDE).

PAS1192 and BS1192 describe a Common Data Environment (CDE) as the single source of information for the project, used to collect, manage and disseminate documentation, the graphical model and non-graphical data for the whole project team. Creating this single source of information facilitates collaboration between project team members and helps avoid duplication and mistakes. A CDE is thus a collaborative environment that everyone uses, following the guidance given under, to coordinate information with supply chain members on the project. A CDE can be a collection of linked distributed sub-CDE’s.

A schematic architecture that can be further developed towards a CDE architecture is shown in the following figure. In the scheme, the orange-coloured block at the bottom represents raw data; the blue-coloured blocks at the centre represent the solutions for processing and managing data, and the user interface (including the GUI – Graphical User Interface); the green-coloured block at the top represents a specific toolset or methods which are used by the civil infrastructure experts.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

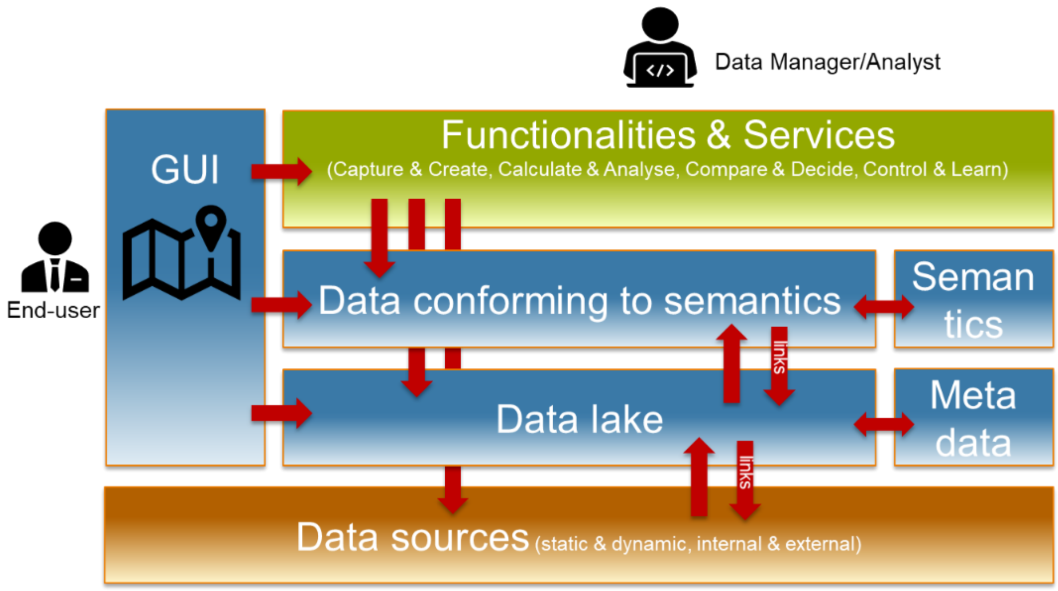

Figure 4.6 – Conceptual architecture for data integration (Bohms, 2019).

The data sources are various and they can include 'static' object data and 'dynamic' monitoring data from sensors, as well as documents either structured or unstructured, and files in any format. Depending on the project or asset management purpose, a selection of data is put into the Data Lake. The selection and transfer of data from the Data Sources to the data lake can be performed through several methods, for instance: via import/export (over the web: download/upload); via links or direct access without copies utilizing URIs, APIs, query languages etc.; or via direct real-time streaming of data from a measurement system involving sensors and/or actuators in reality. In the Data Lake, the data can be enriched/annotated by adding meta-data reflecting its source, status, precision etc. Typically it is also given some explicit context, such as a position in time and space that is often implicitly available in its original folder/file name. For certain data, the meaning or semantics can be made explicit in schemas, ontologies, etc. On the technology, the use of W3C Linked Data technology –where data is in standard triple (RDF) forms and semantics is provided by ontologies– is recommended. With this, non-linked data can be referenced and all data can be directly accessed via SPARQL or front-ends, such as GraphQL-LD. Finally, all data (data sources, annotated data, semantic data) can be accessed by Functionalities and Services, which are the relevant expert software, tools, methods or algorithms depending on the objectives of the project and the analysis.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

5. Data security

5.1 Introduction

Data security or Information Security (InfoSec) is a vast and fundamental topic in information technology whose scope and applicability goes beyond the scopes of this project. The aim of this chapter is to give a coarse overview of the main concepts and principles that are most relevant for this document.

The fundamental principles in data security are known as the "CIA triad" (Dhillon, 2001): *confidentiality*, *integrity*, and *availability*.

Figure 5.1 – The CIA triad of information security (image from (Purcell, 2018))

- **Confidentiality** is concerned with preventing unauthorized access to sensitive data. The two main ways to guarantee confidentiality are *data encryption* (which prevents unauthorized access by rendering the data unusable by anyone other than an authorized user), and *data access control* (which, analogously to *physical access control,* selectively restricts access to data to a set of authorized users who can exhibit appropriate *credentials*).
- **Integrity** is concerned with assuring the accuracy and completeness of data over its entire life-cycle (Boritz, 2005), and in particular protecting protecting data from improper modification, including:
  1. modification of data by unauthorized users
  2. unauthorized or unintentional modification of data by authorized users
  3. loss of data consistency.

  More generally, integrity from a broader information security perspective touches upon aspects that have to do with guaranteeing credibility, completeness, accuracy and trustworthiness of the data (Sebastian-Coleman, 2012).
- **Availability** has the goal of ensuring that authorized users have uninterrupted access to the data that they needed. Ensuring availability also involves preventing service disruptions due to hardware failures and power outages, as well as cyber attacks such as denial-of-service attacks (Loukas, 2010).

As mentioned, data availability is a key principle in data security. The topic and how it relates to cybersecurity is however so vast and fundamental in every industry to be markedly beyond the scope of this document, and is on the other hand the object of other EU initiatives, such as the European Cyber Security Organization (ECSO) that elaborated some

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

recommendations for an increased European CYbersecurity Sovereignty and Strategic Autonomy (ECSO, 2021). We also refer to other excellent external resources such as the NIST Cybersecurity Framework (National Institute of Standards and Technology, 2018), which is a set of guidelines for mitigating organizational cybersecurity risks, published by the US National Institute of Standards and Technology (NIST), and the most recent Threat Intelligence Index published by the IBM Security X-Force Research team (IBM Security X-Force, 2022), which includes an in-depth analysis of the main cybersecurity threats, industry trends, risk mitigation recommendations, and best practices and industry solutions.

5.2 Risk management strategies

Organizing a data security strategy from scratch is a daunting task for any organization. Fortunately, there are very valuable public resources that can be used as a first step in designing a strategy around evaluating risks and planning mitigation stategies that optimize cybersecurity investments. One such resource paramount resource in information security is the NIST Cybersecurity Framework (National Institute of Standards and Technology, 2018). The core material of the the NIST framework is organized in five major functions:

Figure 5.2 – The five major functions of the NIST Cybersecurity Framework (National Institute of Standards and Technology, 2018)

- **Identify**: This function calls for an understanding and documentataion of the cybersecurity risks tied to an organizations systems, people, assets, data and capabilities. Understanding the business context, the resources that support critical functions, and the related cybersecurity risks enables an organization to focus and prioritize its efforts, consistent with its risk management strategy and business needs.
- **Protect**: This function has the goal of developing appropriate security controls and other safeguards to ensure that the most critical assets of an organization are preotected against cyber threats. This function also supports the ability to limit or contain the impact of a potential cybersecurity event.
- **Detect**: This function consists in ensuring the deployment of appropriate activities to rapidly identify the occurence of events that could pose a risk to an organization data security.
- **Respond**: This function aims to procedures in place to enable prompt response to contain cybersecurity incidents as soon as they have been detected.
- **Recover**: This function calls for the identification and implementation of resilience plans to quickly restore data and services of an organization that has been impacted by a security incident. This will support timely recovery to normal operations to reduce the impact from a cybersecurity incident.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

5.3 Data Access Control

Together with cryptography, Data Access Control is a key component to implement the protect function of risk management strategies that aim to address the confidentiality and integrity principles of the CIA triad. The way Data Access Control achieves that is by guaranteeing that only authorized users with appropriate credentials have read and write access on the data.

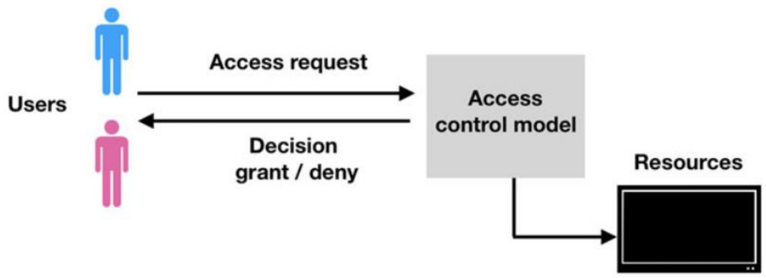

Figure 5.3 – Access control (Andress, 2014)

Data Access Control is based on three key mechanisms: identification, authentication, and authorization (Leech, 1996).

Figure 5.4 – Basic mechanisms of Data Access Control (Leech, 1996)

- **Identification** is an assertion regarding someone's identity. Typically this assertion is in the form of a username, which is being entered in a login interface (Musa, 2014).
- **Authentication** is the set of methods used to establish the veracity of a claim of identity. In this strict sense, authentication only establishes whether the claim of identity that has been made is true, and does not imply anything about what the authenticated user is allowed to access on the system, which is on the other hand part of the mechanism of authorization. Together with a username being commonly used as a form of identification on computer systems, a password is the most common form of authentication. In terms of authentication, several types can be used alternatively or concurrently. A type of authentication is referred to as *factor*, and the more factors are being used concurrently, the stronger the authentication is considered to be.
- **Authorization** specifies what an authenticated user is allowed to do on the system. Once a user is authorized the resources they will have access to will be determined and enforced by the Access Control Model that is being used on the system. There are four major Access Control Models (Hu V.C., 2013):
  1. **Attribute-based Access Control (ABAC)**, which is an access control paradigm where access rights are granted to users through the use of policies which evaluate attributes (user attributes, resource attributes and environment conditions) (McAfee, 2019);
  2. **Mandatory Access Control (MAC)**, which is an access control model where users don't have much freedom to determine who has access to their files, but access capabilities are rigidly predefined and established by administrators. This model is notoriously inflexible, but also considered the most secure access control model.
  3. **Discretionary Access Control (DAC)**, where the data owner determines who can access specific resources. For example, a system administrator may create a

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

hierarchy of files to be accessed based on certain permissions. Permissions refer to the access modality that a user can attribute to specific data objects. They allow the user to access data in a specific mode, for example, read or write. Users access rights are then determined by an access matrix relating users, data objects and corresponding permissions.

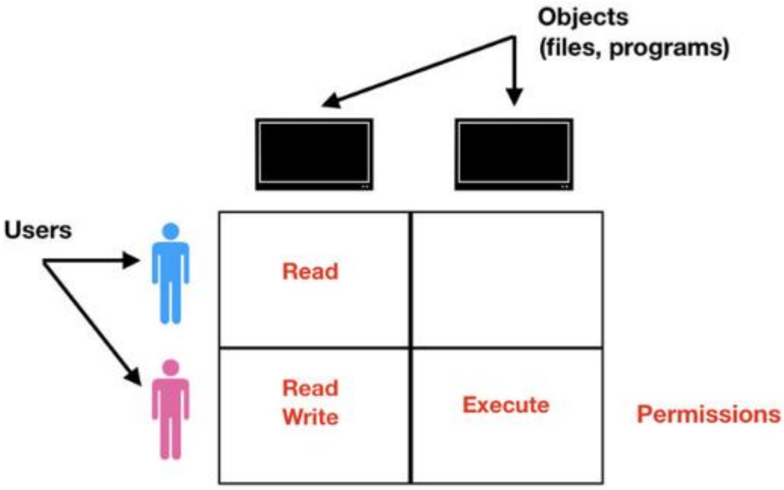

Figure 5.5 – Access matrix model of Discretionary Access Control

4. Role-Based **Access Control (RBAC)**, which largely eliminates discretion by allowing access based on the role or job title of users. Crucially, in this model users cannot pass their permissions to other users, which is a main difference between RBAC and DAC. However, in RBAC roles can be organized in a "role hierarchy", such that parent roles can implicitly contain other roles and inherit the permissions of their descendant roles.

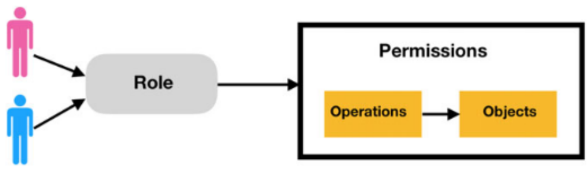

Figure 5.6 – Role-Based Access Control

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

The following table enumerates the advantage and disadvantages of the mentioned *Access Control Models:*

ACM	Advantages	Disadvantages	Applications
MAC	Scalable Secure Full control by administrators only	Hard implementation Relies on system to control access Not flexible Supports limited number of users	Government organizations Military Critical missions
DAC	Easy implementation Highly flexible Protect users from unauthorized access	Prone to errors Relies on object owner Not scalable Susceptible to Trojan horse attacks Difficult in maintenance and verification	Web applications OS: Linux, Unix, Netware Critical missions
RBAC	Easy implementation Hierarchy and rights inheritance Duties separation Scalable Highly secure	Hard to manage and maintain Hard to implement fine grained access control Prone to errors	Health care systems Academic institutions Banking systems
ABAC	Single point provisioning of users Dynamic access control Fine-grained access control	Lack of requirements Complex authorization ownership Complex auditability Complex delegation Hard scalability	Government organizations Health care systems Airlines companies Insurance systems Telecommunications carriers

Figure 5.7 – Advantages and disadvantages of Access Control Models (ACMs)

5.4 Data security issues in cloud computing

By offering flexibly on-demand access to computing resources, applications, data storage, and networking capabilities, cloud computing is a technology that represent an incredible opportunity across industries. One downside of this new way of accessing IT infrastructure is the corresponding increase in threat surface and a set of new information security challenges. It is worth noting however that the industry was very quick at raising to the challenge, and already in 2020 the majority of companies reported experiencing better security in the cloud than on-premises.

In this section we examine some of the data security issues that emerge or are of particular interest specifically in the case of cloud computing infrastructures compared to legacy IT environments.

5.4.1 Cloud security best practices

Maintaining security of systems deployed on the cloud demands different procedures and than in more traditional IT environments. The main cloud security best practices include the following (Vennam, 2021):

- **Security and compliance monitoring**: The first step and prerequisite to deploy one's system on cloud infrastructure is to understand all regulatory compliance standards applicable to the specific industry where one is operating, and setting up active monitoring of all connected systems and cloud-based services to maintain visibility of all data exchanges between all cloud environments.
- **Shared responsibility for security**: Generally, cloud providers are responsible for securing cloud infrastructure and the customer is responsible for protecting their data within the cloud. But it's also important to clearly define data ownership between private and public third parties.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.

- **Data encryption**: Data should be encrypted while at rest, in transit, and in use. Cloud infrastructure customers need to maintain full control over security keys and hardware security module.
- **User identity and access management**: Customer and IT teams need full understanding of and visibility into network, device, application, and data access.
- **Collaborative management**: Proper communication and clear, understandable processes between IT, operations, and security teams are essential to ensure seamless cloud integration that is secure and sustainable.

5.4.2 Data Security Issues of Cloud Data Life Cycle

In cloud infrastructures *data storage* is typically distributed over multiple data centers and *data processing* can happen in virtual machines that are also being deployed across possibly multiple physical servers. This geographically distributed character of cloud computing comes with its sets of new regulatory and security considerations, since transfer of data calculation and storage to a third part involves the transfer of responsibility associated with their security and compliance to this third part (Singh VK, 2016) (Kacha L, 2018).

The processes involved in distributing storage and data processing across servers implied in on-cloud data processing can be broken down into three distinct states relating to the data in a cloud infrastructure, each one with its specific security risks:

- **Data-at-rest**, where the data is stored in a low cost but high latency medium-low. Data-at-rest in cloud computing is subject to risks that fall into three categories:
    1. *Risks associated with storage media sharing,* which stem from the fact that physical infrastructure is shared between different users, meaning that a security breach might simultaneously affect multiple users (Singh S, 2016).
    2. *Risks associated with data location,* which derive from the fact that data is potentially stored in different locations distributed around geographies. In this case, users have to be aware of the consequences of their data being located in specific locations, like the fact that they are subject to the local laws that might confer to the local authorities to access the data under given circumstances.
    3. *Risks related to storage media reliability,* this risks come from the fact that users do not control physical access to data on a cloud storage platform. This means that users will depend on the cloud provider to secure their data, and guarantee availability.
- **Data-in-transit**, which denotes data being transferred for instance from storage to a processing virtual machine, and back. Data-in-transit are typically subject to higher risks than data-at-rest, because data relocation compounds the *risks associated with data location* across all the locations across which the data transits. Secondly, risks associated with data transmission have to be considered (see following section “Requirements for fast and secure data transmission”).
- **Data-in-use**, which refers to data being accessed and processed. When data is being processed on cloud infrastructures, the risks of misuse increase, due to the large number of users being hosted on the same infrastructure. An example of such threats is a problem known as *data remanence*, which refers to the fact that upon deletion data residues might still persist on the cloud infrastructure. Consequently, subsequent users gaining access to the same physical storage resources could in principle be able to restore the data.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958171.

5.5 Storing, managing and sharing the data

5.5.1 Technical specifications

In order to store data, there exist secure options offered by various cloud providers. Typically, object stores are encrypted by default. Data at rest is encrypted with Advanced Encryption Standard (AES) 256-bit encryption and Secure Hash Algorithm (SHA)-256 hash. The encrypted keys used for data in motion can also be used to handle data at rest and can either be managed by the data owner itself or by using key protection software. Access control rights can be implemented at the level of each encrypted key, thus allowing specific users to have read, write or both read/write access to the data. In case the data to be stored has different owners, modalities, etc., it is possible to use containerization techniques to store and manage the data across different containers and buckets. The management of these containers and buckets can be done via platforms like Kubernetes. Bucketing data also allows to: 1) keep track of versioning (i.e., different versions of data, in terms of collection timeframes, modalities, etc.), and 2) perform data management operations (i.e., delete old versions of the data, manage updates, merge data, etc.).

5.5.2 Regulatory concerns

5.5.2.1 Personal data protection

The General Data Protection Regulation (GDPR) is a European Union regulation that has been mandatory since May 2018 and regulates the protection of the data of citizens residing in the EU. This law affects, in general, all companies that collect, store, process, use or manage any type of data of EU citizens. The law includes, for example, the right to be forgotten, the right to portability or the right of access (knowledge of whether, where and for what purpose data relating to a citizen is being processed). Personal data is any information relating to a natural person that can be used to identify him or her directly or indirectly, such as a name, a photo or an IP address.

When scanning and monitoring assets, no personal information of any kind is stored in any database, as this is irrelevant to the purpose of the activity being carried out. However, there could in theory be an indirect collection of personal information when monitoring public spaces. This particularly involves the collection of images, which constitute sensitive data under the GDPR when they make a person or number plate identifiable.

Article 89 of the GDPR covers the processing of personal data when they are collected for archiving purposes in the public interest, scientific or historical research purposes or statistical purposes. In these cases, the collection and processing of data is possible although it must be subject to appropriate safeguards for the rights and freedoms of data subjects in the forms set out in the law. It is especially critical to follow the principle of minimisation of personal data.

Given that in infrastructure scanning and monitoring the collection and processing of personal information that can be extracted from the captured images is totally unnecessary for the desired purpose and following the principle of minimisation of personal data, the following lines of action are advised:

a. Pictures should preferably be recorded or captured in such a way that no identifiable persons or number plates appear in the images.
b. Captured images shall have faces and number plates blurred or removed prior to storage, with the exception of temporary storage while awaiting processing.

The first point is difficult to comply with since the traffic of vehicles or persons should be interrupted as little as possible during the monitoring work; and collecting images without the appearance of persons or number plates may be impossible or more costly than deleting them once they have been captured. Therefore, usually the second point will be preferred instead.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

5.5.2.2 Storage on servers located in the EU

As long as the stored data does not contain personal information, there is no obligation for the data to be stored on a server in the EU. However, there are several reasons why it is advisable to do so:

- The data collected on key transport infrastructures in the European Union, particularly data that might highlight possible damage or structural weaknesses in them, constitutes sensitive information for maintaining the safety and availability of the movement of passengers and goods on Europe's main routes. Although these data are protected by mechanisms that prevent access by unauthorised entities, the very storage of the data on servers in third countries is an obstacle to their protection.
- Regardless of whether it makes sense to store data where it is generated and used, the European Union is particularly protective of personal and non-personal data concerning European citizens and entities and has tougher EU regulations than most states. These regulations, which affect servers established in the EU, favour the users of such services.
- Data from European infrastructures will normally be accessed from within the EU, so closer proximity of servers to the devices accessing them will reduce the time it takes to load or download information.

In short: keeping data obtained from EU infrastructures on servers located in the EU will allow for a more secure, faster data infrastructure with more control over its sovereignty.

In order to ensure that data is stored on a server located in the European Union, there are two options:

a. Setting up servers dedicated to host the databases and services that give access to the information collected to the bodies concerned.
b. Contract the hosting to companies that ensure in their terms that all data is stored in the EU. It is also advisable that these companies are themselves European, which ensures that they respond primarily to European regulations.

Some checks may be useful to verify that the server being used to host or access the data is located in the European Union. It is important to note that:

- The domain of a website (.com, .eu, .nl, .es...) has nothing to do with the location where it is hosted.
- Although the location of the server where a service or web page is hosted may be known, it may be making use of a database hosted in another territory.

To check the location of the server where a service or web page is hosted by knowing its IP address, and from there to find out where it is registered, the following steps can be followed:

1. If the IP of the server is not known, it can be obtained by using the command traceroute in the Linux Terminal or tracert in the Windows Console, followed by the domain name. However, the domain manager may direct to different servers depending on demand or other circumstances.

2. 2. Knowing the IP address of the server, it can be entered into an IP tracing database. Several websites perform this service, e.g. WolframAlpha.com. This will show the location of the IP address registrant.

5.6 New technologies

Blockchain technology is a new tool used to record transactions and link them together to form a so-called “chain” that is known as a distributed ledger. Specifically, this ledger is a collection of transactions, contracts and operations stored in chronological order and in a decentralized fashion. Once published, the information on the blockchain cannot be altered. Within a project,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

this chain can be thought of as a literal chain, each link being a separate transaction in the project. For instance, if one supplier completes a delivery and fulfils their contract, the completed contract is finalized and added as a new "block", or link in the chain. This gives blockchains a natural order that is easy to follow when looking for information.

Blockchain technology is mot benecial in industries and scenarios where there is no single central party that is accepted and trusted by all other players to have full authority and power of decision.

Blockchain is characterised by three main principles, namely security, decentralization and scalability.

a) **Security**: Multilayer encryption using mathematical functions hides data in a coded string of characters that are difficult to crack.

b) **Decentralization**: Connections called "nodes" automatically check transactions, leading to a digital paper trail of verified records.

c) **Scalability**: Because information stored in blockchains is not stored on a central server or system, blockchain can be scaled to fit large projects, not only small.

While blockchain technology has many implications for a variety of industries, in the civil engineering industry, it can significantly streamline project management. It is in fact not uncommon that this industry is regarded as one of the most fragmented, high impact sectors and it has been regularly challenged to improve its efficiency, productivity and to embrace the opportunities presented by emerging technologies. For example, communication between builders, vendors and laborers can delay completion timelines. By adopting blockchain, the civil engineering industry can benefit from a few immediate benefits.

1. **Streamlined supply chains**

Procurement can become particularly tedious when dealing with complex projects, that involve players like airports or hospitals. Using a decentralized blockchain network and inviting suppliers to be a part of it, allows project managers to track materials throughout the entire project, and even ensure the efficient utilization of those materials. The blockchain could also incorporate construction equipment to manage rental timelines or depreciation costs.

Digital keys function as unique IDs for one party in a blockchain network. In civil engineering, assigning keys to vendors would allow their work to be tracked through the blockchain. This would create a permanent work portfolio that could be used to appraise vendors for projects.

2. **Predictive asset maintenance**

It is estimated that a vast majority of the information about a construction project is lost in the transition to the completed project's first owner. The distributed ledger in blockchain can store lifecycle information about every asset in a building project, like warranties, certifications and replacements.

Using Building Information Management (BIM) technology, an immutable, digital replica of the construction project is set up within the blockchain. This acts as a model to ensure the project is within scope. In additon it serves as a virtual home for assets so they can be easily searched and quantified. The provenance of the materials can reduce waste and drive quality of products and service forward with high accountability. Therefore, storing and using all this information in the blockchain can enhance predictability with regards to procurement, as well as in the case of the whole project delivery. Together with BIM, blockchain can create the single source of truth for all aspects of a civil engineering project. Such a model can become the trusted digital twin

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

of an asset supporting tnot only its design and construction, but its operation and maintenance along the whole lifecycle, especially when coupled with artificial intelligence. The use of such complex models can provide detection of defects and their risk through automated visual inspection, and can support experts in planning the appropriate maintenance and repair operations and their timelines.

3. Smart contracts

Smart contracts infuse blockchain technology into traditional, written agreements. Because data is decentralized and readily available throughout the network, the need for document duplication is eliminated. All contracts live in the blockchain and are accessible with a simple search. The sequential nature of a blockchain setup holds contractors accountable by requiring a project to meet specifications, or else the contract is unfulfilled. Change orders and delays are immediately traceable to a point of origin, eliminating the need for time-consuming oversight.

Through smart contracts, business processes and administrative tasks can be automated to increase efficiency and always be aligned with the agreed contractual terms. This can result in significant cost savings, increment in the low margins of the industry, and better control project costs.s

4. Proactive third-party oversight

When dozens of subcontractors are hired to complete tasks, additional oversight is needed to ensure a complex project will adhere to local standards and regulations. This might be legal consultation to comply with government regulations, safety management to monitor worksite processes or union representation to advocate for site workers. For projects that adopt blockchain technology, these third parties can be seamlessly integrated into project oversight. They have access to crucial documents from the moment they are included in the blockchain, reducing time wasted in submitting information requests.

5. Accelerated payment processing

Processing payments via blockchain is free in most cases. No authorization or processing fees mean faster payments and less back-and-forth. Blockchain's strict boundaries, enforced with smart contracts, ensure payment is received for work that is completed according to the project framework. By reducing late payments, remediations and disputes, small and medium enterprises are no longer placed in continuous cash flow risk. Smart contracts work on milestones, so when each milestone is achieved, payments will automatically proceed. The blockchain framework ensures that work is completed to specifications, and the hassle of authorizing or collecting payment is nonexistent. Payment automation additionally reduces overhead and cost overrun.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

6. Bibliography

Alonso, A. a. (2018). Industrial data space architecture implementation using FIWARE. *Sensors*, 2226.

Andress, J. (2014). *The basics of information security: understanding the fundamentals of InfoSec in theory and practice.* Syngress.

Bohms, H. S. (2019). Selection of a data storage, management and analysis ecosystem for SR, TNO report.

Boritz, J. E. (2005). IS practitioner' views on core concepts of information integrity. *International Journal of Accounting Information Sysstems, 6*(4), 260-79.

Buziek, G., & Mundt, M. (2022). *Smart Infrastructure Management*. Obtenido de https://www.data-infrastructure.eu/GAIAX/Redaktion/EN/Artikel/UseCases/smart-infrastructure-management.html

CORDIS. (2019). *Digital Platform for Construction in Europe*. Obtenido de CORDIS: https://cordis.europa.eu/project/id/856943

Denmark, C. (2021). European Construction Sector Observatory.

Dhillon, G. B. (2001). Current directions in IS security research: towards socio-organizational perspectives. *Information Systems Journal, 11*(2), 127-53.

DigiPLACE. (2021). *TOWARDS A EUROPEAN DIGITAL PLATFORM FOR CONSTRUCTION*. Obtenido de https://www.digiplaceproject.eu/

ECSO. (2021). *Initial recommendations and actionsfor an increased European Cybersecurity Sovereignty and Strategic Autonomy (CYSSA).* European Security Organization.

EU Comission. (2021). *Building a data economy — Brochure*. Obtenido de https://digital-strategy.ec.europa.eu/en/library/building-data-economy-brochure

EUComission. (2018). *A European Strategy for data*. Obtenido de https://digital-strategy.ec.europa.eu/en/policies/strategy-data

Fiware. (2022). *Smart Industry - Fiware*. Obtenido de https://www.fiware.org/community/smart-industry/

Gaia-x. (2022). *Gaia-x.eu*. Obtenido de https://www.gaia-x.eu/

GoFair. (2022). *GoFair*. Obtenido de https://www.go-fair.org/

Hu V.C., F. D. (2013). Guide to attribute based access control (abac) definition and considerations (draft). *NIST special publication, 800*(162), 1-54.

IBM Security X-Force. (2022). *X-Force Threat Intelligence Index 2022*. Obtenido de https://www.ibm.com/security/data-breach/threat-intelligence/

International Data Spaces. (s.f.). Obtenido de https://internationaldataspaces.org/

Kacha L, Z. A. (2018). An Overview on Data Security in Cloud Computing. In: Silhavy R, Silhavy P, Prokopova Z, editors. Cybernetics Approaches in Intelligent Systems. (S. I. Publishing, Ed.) 250-6.

Leech, M. (1996). *Username/Password Authentication for SOCKS V5.* Internet Engineering Task Force. Obtenido de https://datatracker.ietf.org/doc/rfc1929

Longo, M., Sánchez-Rodríguez, A., Negri, S., Sanecka, P. Z., Marchiori, C., Rigotti, M., . . . Riveiro, B. (2022). *Review of methodologies and instruments for diagnostics of transport infrastructure.* IM-SAFE.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. © 2021

Loukas, G. Ö. (2010). Protection against denial of service attacks: A survey. *The Computer Journal, 53*(7), 1020-37.

McAfee. (2019). *New McAfee Report Finds Eighty-Seven Percent of Companies Experience Business Acceleration from Use of Cloud Services.* Obtenido de https://www.businesswire.com/news/home/20190617005945/en/New-McAfee-Re

Musa, S. (2014). *Cybersecurity: Access Control*. (T. EvoLLLution, Editor) Obtenido de https://evolllution.com/opinions/cybersecurity-access-control/

National Institute of Standards and Technology. (April de 2018). *Framework for Improving Critical Infrastructure Cybersecurity, Version 1.1*.

Purcell, A. (2018). 3 key ideas to help drive compliance in the cloud. (C. C. News, Ed.)

Real Decreto 1098/2001. (s.f.). *Real Decreto 1098/2001, de 12 de octubre, por el que se aprueba el Reglamento general de la Ley de Contratos de las Administraciones Públicas. Artículo 131*.

Sebastian-Coleman, L. (2012). Measuring data quality for ongoing improvement: a data quality assessment framework. (Newnes, Ed.)

Singh S, J. Y.-S. (2016). A survey on cloud computing security: Issues, threats, and solutions. *Journal of Network and Computer Applications, 22*, 75-200.

Singh VK, S. T. (2016). Present data security issues and their resolving technique in cloud computing. *International Journal of Science and Technology, 1*, 1-6.

Vennam, S. (2021). What is Cloud Computing? Obtenido de https://www.ibm.com/cloud/learn/cloud-computing

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171.