Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Requirements for next generation monitoring and inspection

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EXECUTIVE SUMMARY

This report is the first deliverable for Work Package 4.2 under Sub- Project 4 (SP4) of the Capacity4Rail project.

The aim of this deliverable is to set out the basis for the selection of the most suitable components of the monitoring system, such as devices, methods and tools, to be integrated in upgraded and new infrastructure elements leading to the achievement of the general goals of the Capacity4Rail project, i.e. the design and development of an affordable, adaptable, automated, resilient and high capacity railway system.

First of all, a set of functional and technical requirements at low level, mid level and high level has been defined. Once scored, the features of the monitoring components can be assessed together with their cost in an evaluation framework (spreadsheet) developed to this end, giving the best value to the solution that better meets the functional and technical requirements at minimum cost.

This methodology will be helpful in the work to be done in Tasks 4.2.2 and 4.2.3, in charge of the selection of sensor, energy harvesting, communication and data integration technologies.

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ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
C4R	Capacity4Rail
RMS	Root Mean Square
ICT	Information and Communication Technology
TMS	Traffic Management System
CMMS	Computerized Maintenance Management System
LCC	Life Cycle Cost

1 INTRODUCTION

One of the very first tasks of CAPACITY4RAIL is to define a comprehensive roadmap to describe the necessary steps to develop and implement innovation and to progress from the current state-of-the-art to a shared global vision of the 2050 railway along realistic scenarios.

Five major requirements have been defined for all the developments within this project: The future railway system should be affordable, adaptable, automated, resilient and high capacity.

Monitoring systems currently in use on railways are passive in the sense that only when a significant defect occurs the system reacts and report to the maintenance manager. But outside the railway industry, advanced monitoring technologies are already in use, including modern ICT techniques to analyse gathered data in real-time (big data, cloud computing) and processing tools to anticipate defects and predict its evolution (degradation models). Learning from other industries, CAPACITY4RAIL is investigating ways to implement such tools into both future and existing infrastructures, and to develop associated strategies for a non-intrusive and highly automated monitoring.

In order to accomplish with the general goals of the project by considering the wide variety of monitoring technologies currently available, a set of functional, technical and economical requirements are defined. Once described this requirements in a quantitative way, the evaluation framework will allow in subsequent tasks the assessment of the monitoring solutions to select the one that better meets the requirements and presents the lower cost.

2 OBJECTIVES

The objectives of SP4 – WP4.2 *Monitoring Technologies & Sensors* are:

1. Development of *functional and technical requirements* which are able to steer technology that is considered in later tasks.
2. *Identification and evaluation of sensors and energy harvesting technologies* that address the requirements developed before.
3. *Identification and evaluation of communication and data integration technologies* that address the requirements developed before.
4. Demonstration of innovative monitoring concepts in the laboratory.

This report addresses objectives 1: it includes low-level, mid-level and high-level requirements for sensor, energy harvesting, communication and data integration technologies, as well as an evaluation framework for use in the following tasks.

The structure of this report is shown in Table 1.

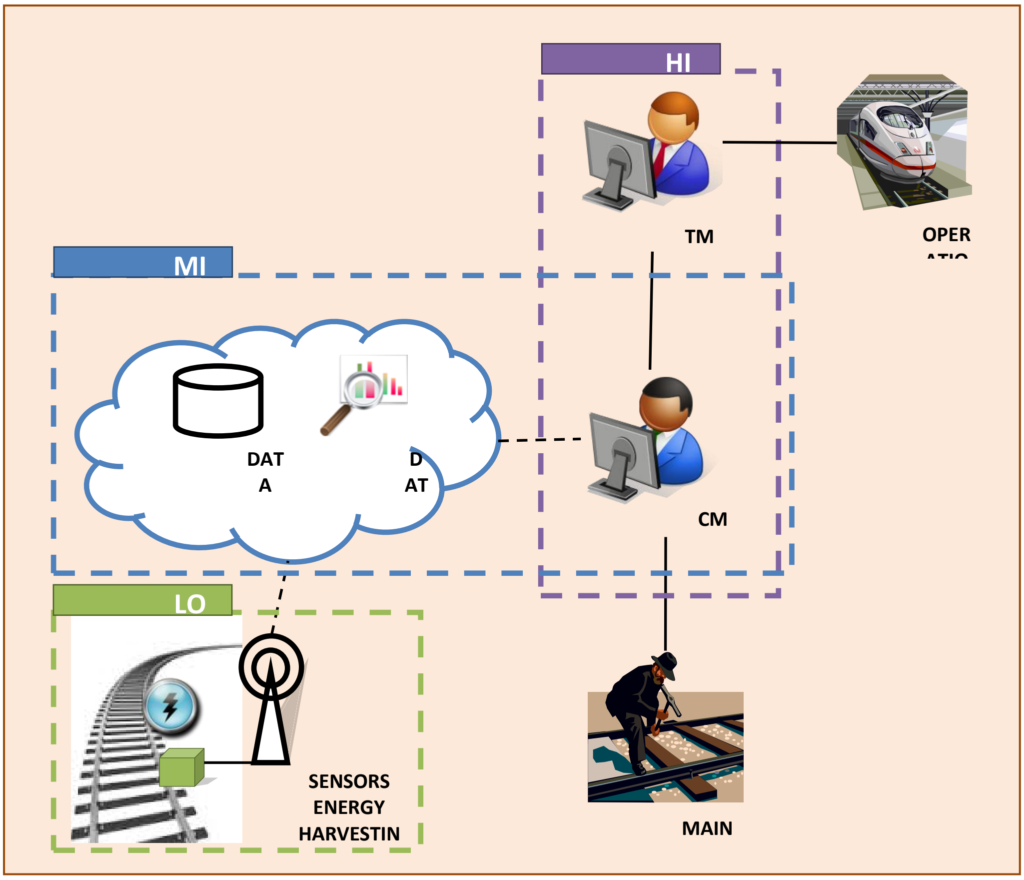
Table 1: Structure of this Report

Chapter	Title	Content of Chapter
1	Introduction	
2	Objectives	The objectives of WP4.2 and this report.
3	Context	Relationship between requirement levels
4	Low level requirements	Related to tasks where direct measurements are required.
5	Mid level requirements	Related to condition monitoring: fault detection and diagnosis.
6	High level requirements	Related to system state observations, used at the operational level of the railway.
7	Evaluation framework	
8	Conclusions	
9	References	

3 OVERVIEW

Three application levels have been considered in monitoring, each with some differing requirements.

- **Low level** deals with inspection applications. It correlates directly with the physical measurement process, for example to fulfil a safety related check. Technologies involved at this level are **sensors**, **communication**s and **energy harvesting**, as well as any hardware to be physically implemented in or close to the monitored area. Requirements to be defined are related to the measurement features, such as acquisition rates and data transfer capabilities.
- **Mid level** deals with **data management and processing**, from the raw recorded data to the evaluation of asset condition. Technologies involved are the data storage and the algorithms for fault detection, diagnosis and prognosis. The requirements will be related to storage and calculation capabilities, as well as the number and type of inputs to make the algorithms work.
- **High level** deals with the outputs of the whole monitoring system and the **interface with third party software** owned by Infrastructure Managers, such as Computerized Maintenance Management Systems or Traffic Management Systems. These set of requirements will describe what is needed to allow operational decisions to be made.



A total amount of 39 requirements have been identified for the whole monitoring system: 16 at low level, 18 at mid level and 5 at high level. Next table shows the classification of these requirements at each level, grouping into subsystems when appropriated.

LOW LEVEL REQUIREMENTS (In-field inspection / Hardware)	MID LEVEL REQUIREMENTS (Data management, algorithms)	HIGH LEVEL REQUIREMENTS (Data integration / Third party software)
SENSORS (data acquisition) Functionality Automated data collection Detection of incipient faults Event localization Weak up under event Scalability Environmental compatibility Data collection at line speed (only embarked sensors) Different measurement modes Configuration Custom reporting of parameters Custom fault detection rules Custom submission rate of measurements Self-diagnostic Sensing Long term stability Long term robustness and reliability Installation and maintenance Calibration Geometrical compatibility with the monitored infrastructure element Compatibility with track maintenance High availability on component level High availability of sensor node Resistance to electromagnetic fields	**DATA AGGREGATION, FUSION AND STORAGE** Data aggregation and signal analysis Time Synchronization Spatial synchronization (only embarked sensors) Data security & integrity Data analysis speed Big data capabilities Cloud computing **FAULT DETECTION (Defect recognition)** Real-time data processing Custom fault detection rules at system level Adaptable methods and tools for data analysis Extreme Learning Machine approach **DIAGNOSIS (Evaluation algorithms)** Instant access to historical data Deterministic approach to diagnosis **PROGNOSIS (Degradation algorithms)** Advanced modelling for track degradation Instant access to cumulative track loads Auto-adjusting of degradation models	- Geographically referenced data - Interoperability with other railway subsystems - Ontology based standard Railway Data Model - Standard protocol to access external databases - Web-based storing and application systems

LOW LEVEL REQUIREMENTS (In-field inspection / Hardware)	MID LEVEL REQUIREMENTS (Data management, algorithms)	HIGH LEVEL REQUIREMENTS (Data integration / Third party software)
Mounting simplicity **ENERGY HARVESTING (generation/storage)** Suitability for installation at different sites Monitoring and reporting of battery status Self-diagnostic Environmental compatibility Resistance to electromagnetic fields Mounting simplicity **COMMUNICATIONS** Fast data transmission Wireless communication Standard interface for wireless Industrial Ethernet communications interface Custom message format for internal communications Time synchronization	Defect prediction Report of stochastic information to the decision support system	

4 LOW LEVEL REQUIREMENTS

4.1 Sensors (data acquisition)

Sensing systems correspond with lowest level of the overall of the monitoring system structure; the overall operation of the monitoring system of the railway infrastructure depends on the performance of such sensors.

Therefore it is important to define the requirements for measuring devices installed along the infrastructure to monitor. Operating, installation and maintenance characteristics must be described in order to identify whether a system is easy to install and maintain or not.

Among the most important requirements for the data collection devices are important to note: Automatic data collection, customizable thresholds and alarms, adaptability of sensors to different environments depending on routes, location and type of expected traffic.

Next, these specifications are explained in a more detailed way, structured according to the nature of the described requirement.

4.1.1 Functionality

Functionality refers to the way the system works in order to achieve the planned targets. Any kind of performance and feature done by the system will be described in this chapter.

4.1.1.1 Automated data collection

Monitoring system shall be able to collect performance and condition data without human intervention. Doing so, there are fewer possibilities to make a mistake or any personal influence on the measurement process. Besides the costs of data collection will be reduced.

Data collected by sensors devices shall be periodically sent to the data management systems for treatment. The desired objective is that the entity responsible for the maintenance of the railway infrastructure has updated, reliable and quality information for decision making on maintenance planning.

RATING

DESCRIPTION	Score
Fully automated data collection	10
Requires human intervention only to start and/or stop the measuring process.	5
Manual data collection	0

4.1.1.2 Detection of incipient faults

The sensors should not only measure when detecting a fault over thresholds, but also when at the early stages of development with the aim of scheduling maintenance actions before the failure occurs and with minimum cost.

To this end, the sensor should be accurate enough and it should be able to measure very frequently or even continuously, but always bearing in mind autonomy that batteries and harvesting system can provide.

RATING

Description	Score
The accuracy and data acquisition rate of the sensor allows the detection of incipient faults	10
The accuracy or the data acquisition of the sensor does not allow the detection of incipient faults.	5
Both the accuracy and the data acquisition of the sensor do not allow the detection of incipient faults.	0

4.1.1.3 Event localization

Most sensor data is associated with the physical context of the phenomena being sensed. Hence event localization, that is, the determination of the position of specific events, is an important problem that needs to be solved efficiently for the application at hand.

The use of signal strength techniques for event localization and tracking of moving objects is well-known [1]. But this event localization gives the position of the sensor mote itself. In case of structural health monitoring, the application on fixed structures contains a static network topology, which simplifies the problem, because the sensor positions are well known.

However, if the monitoring task is an acoustic emission analysis with the localization of the damage zone, the sensor positions and the origin of the acoustic event could be differently located and an interpolation must be done. In this case it is useful to integrate some sensor nodes to a cluster. Such clusters or sensor arrays are well known for the localisation of earthquakes or other seismic events and could be used to localize damage processes in structural parts as well.

The use of the measured transient acoustic event and its onset time with the combination of knowledge about the specific positions and the sensing ranges of all nodes in the network would allow locating events very precisely, while at the same time being able to transmit this information using a very low number of packets.

RATING

Description	Score
Cluster level event Location	10
Event location by sensor location	5
No event location	0

4.1.1.4 Weak up under event

In regular conditions, the sensor devices will be in SLEEP state, in this state power consumption is reduced to almost zero.

For every type of sensor, some flags or triggers will be defined; these triggers will cause the device to wake up and go to normal operation, performing the functions specified by each particular trigger.

RATING

Description	Score
Ability to weak up under event and periodically	10
Only periodically wake up	5
Continuous working rate	0

4.1.1.5 Different working period for sensing and sending

In order to optimize the energy consumption by sensor devices, different stages may be identified in their operation. So, there will be times when the device must gather measures and others in which the device will send the data to network. There will be times even where these two periods can match punctually.

Thereby gathering measurements and sending data became independent, obtaining a flexible and optimal system from the point of view of energy consumption.

RATING

Description	Score
Different working and sending periods	10
Same working and sending period	5
Continuous working rate	0

4.1.1.6 Scalability

The system must meet the important feature of scalability, so that we can include additional measurement devices without affecting system performance.

Replacing a device without affecting the overall performance system will be possible, even if the new sensor is different of the previous one. This will extend the areas of measurement and will greatly help in installation and maintenance works.

RATING

Description	Score
High devices density per net (>100)	10
Medium devices density per net (up to 100)	5
Low devices density per net (<50)	0

4.1.1.7 Environmental compatibility

All system components installed on or near the railway shall conform to the requirements of EN 50125-3 (Railway applications. Environmental conditions for equipment. Equipment for signalling and telecommunications).

RATING

Description	Score
EN 50125-3 compliance	10
EN 50125-3 NO compliance	0

4.1.1.8 Data collection at line speed (only embarked sensors)

Sensors selected to be embarked on commercial vehicles shall be able to collect measurements at line speed. When embarked in auscultation vehicles, they shall take measurements at the nominal speed of such vehicle. In any case, defect detection shall be accomplished with the necessary accurateness and reliability.

RATING

Description	Score
Suitable for speed >200 km/h	10
Suitable for speed 100-200 km/h	5
Suitable for speed <100 km/h	0

4.1.1.9 Different measurement modes

Some sensors could inform about the structural integrity of the asset and about train operation. Sometimes, the train passage is necessary to perform the measurements, for example deflections under axle loads or vibrations caused by the train. This kind of sensors has a double function and they are an added-value to the monitoring system in the sense of energy and space savings.

This requirement is in line with the “weak up under event” requirement.

RATING

Description	Score
Structural health and operation monitoring	10
Only structural health monitoring	0

4.1.2 Configuration

To configure the devices will be needed in order to modify their performance according to the specific location or application.

4.1.2.1 Custom reporting of parameters

The maintenance staff should be able to configure the monitoring system so that the report include the standard set of parameters or a selection of certain parameters, complementary to the main measurement, which may be useful in specific cases.

For example, when measuring vibrations the frequency of the first mode shape may be the one to be monitored, but sometimes it is interesting also to know the RMS value or even peak accelerations in a specific direction. All these values could be given by the accelerometer but sometimes they may be or not be necessary.

RATING

DESCRIPTION	Score
Monitoring parameters can be selected remotely.	10
Monitoring parameters can be selected only in-situ.	5
Monitoring parameters cannot be selected.	0

4.1.2.2 Custom fault detection rules

Governments and Infrastructure Managers from different countries may have different reference values, thresholds and sampling rate of measurements. This data should be recorded in the sensor in order to perform fault detection and diagnosis according to the national regulations or special maintenance requirements.

For this reason all values which refer to the way of taking measures will be configured on the device, making possible that the same type of device installed in different locations can work according to different operating parameters, optimizing the use of the device for each specific location or application.

RATING

Feature	Score
Customizable thresholds and sampling rate	10
Not customizable thresholds or sampling rate	5
Not customizable thresholds and sampling rate	0

Although sensors usually have a fixed measurement accuracy given by technology, by the right use of thresholds for error detection values the operation and the measurement acquisition rules can be adapted to the needs of every specific location.

4.1.2.3 Custom submission rate of measurements

The submission rate for measurements taken by the devices will be an important and configurable parameter because the amount of energy consumed strongly depends on the measuring and sending.

The available amount of energy is finite and dependent on generation capacity of harvesting equipment. Therefore it is very important to carry an efficient and intelligent use of energy, by adapting the operation of each device to its specific application.

In this way, optimizing the use of energy will be held thanks to a configurable sending frequency to every sensor device. This particular configuration will be done according to: eventual variations of load patterns (train operation), the criticality or the degradation status of the component, etc.

RATING

Feature	Score
Individual configuration for sending frequency	10
Configuration of sending frequency in Cluster	5
No frequency configuration	0

4.1.2.4 Self-diagnostic

The sensor system should be able to perform self-diagnostic at regular intervals or under demand, giving information about sensors integrity, working conditions, etc.

RATING

Feature	Score
Remote periodical and under demand diagnostic	10
Not periodical or under demand diagnostic	5
No ability for self-diagnostic	0

4.1.3 SENSING

The sensing tasks done by the system must comply with strict requirements about reliability and stability.

4.1.3.1 Long term stability

It specifies the typical long term stability of sensors. Sensors should be suitable for long term monitoring without loss of accuracy

RATING

Feature	Score
Accuracy loss < 2% in 15 years	10
Accuracy loss between: 2% - 5% in 15 years	5
Accuracy loss > 5% in 15 years	0

4.1.3.2 Long term robustness and reliability

The whole monitoring system, which has to be installed on site, has to withstand rough climate and other adverse conditions. For example it has to be resistant against oil, fuel, salt and alkali. The sensors have to be robust and durable such that their measured data is reproducible and reliable over the monitoring period.

RATING

Description	Score
Works on the following range: • Temperature (ºC): -30 ÷ 80 • Relative humidity (%): 10 ÷ 100 • Shock (g): 1000	10
Does not work on the following range: • Temperature (ºC): -30 ÷ 80 • Relative humidity (%): 10 ÷ 100 • Shock (g): 1000	0

4.1.4 INSTALLATION AND MAINTENANCE

All the features and requirements described before have the main target of improving the installation and maintenance tasks of the own sensors. So the requirements related to installation and maintenance are important issues to be considered.

4.1.4.1 Calibration

In case of a defective sensor, the replacement will require a new calibration or at least a mandatory test. The system shall allow recalibration of sensors at the physical location, using portable electronic devices easy to use for any maintenance personnel.

RATING

Feature	Score
Calibration at site	10
Calibration at laboratory	5
No calibration possible, the sensor has to be replaced	0

4.1.4.2 Geometrical compatibility with the monitored infrastructure element

The device shall be able to be integrated in the infrastructure element without major modifications in its designed shape and structure.

RATING

Feature	Score
The sensor requires can be easily integrated in the infrastructure element without any modifications.	10
The sensor requires minor modifications in non-structural parts for its installation.	5
The sensor requires modifications in structural parts of the infrastructure element or for its installation.	0

4.1.4.3 Compatibility with track maintenance

The devices to be installed in rail infrastructure must be compatible with other devices already installed, if any, and also compatible with the maintenance procedures performed, with the aim of maintenance personnel change as little as possible how they perform track maintenance.

RATING

Feature	Score
Track maintenance tasks are not disturbed by the device	10
The performance of track maintenance is slightly reduced by the presence of the device	5
The device has to be dismounted for performing track maintenance and later mounted again.	0

4.1.4.4 High availability on component level

For the development of the sensor devices, will be used robust components in order to extend the reliability and availability of the whole system.

A Mean Time Between Failures (MTBF) higher than 50 years is the target to reach, the minimum admissible MTBF will be 25 years.

RATING

Description	Score
MTBF>50 years	10
MTBF: 25-50 years	5
MTBF<25 years	0

4.1.4.5 High availability of sensor node

The same requirement will be taken in account for sensor nodes, in this case a MTBF higher than 10 years is the target to reach, and minimum admissible MTBF will be 5 years.

RATING

Description	Score
MTBF>10 years	10
MTBF: 5-10 years	5
MTBF<5 years	0

4.1.4.6 Resistance to electromagnetic fields

This subsystem should be suitable for electromagnetically contaminated environments according to the European regulation.

RATING

Feature	Score
The sensor works normally on electromagnetic contaminated environments.	10
The sensor is sensitive to electromagnetic contaminated environment, reducing its performance.	5
The sensor is not able to work on electromagnetic contaminated environments.	0

4.1.4.7 Mounting simplicity

Another important requirement is simplicity in mounting procedures, to look for a plug&play performance is the aim to reach.

RATING

Description	Score
Plug&Play of sensing device and nodes	10
Plug&Play of nodes	5
No Plug&Play	0

4.2 ENERGY HARVESTING (GENERATION/STORAGE)

4.2.1 SUITABILITY FOR INSTALLATION AT DIFFERENT SITES

This feature refers to the suitability of the sensor device to get energy at different environments. For instance, solar panels are only suitable for open spaces (plain track, bridges), at the most at stations. Piezoelectric system for getting energy from vibrations maybe suitable everywhere, even at tunnels, but its performance at stations may be low due to the lower line speed.

RATING

Description	Score
Able to harvest for different sources (Sun light, Magnetic Field, Heat, Vibration), and therefore suitable for installation everywhere (plain track, tunnel, stations, bridges).	10
Able to harvest for a single harvest source, suitable for installation only at open spaces (plain tracks, bridges).	5
Not able to harvest enough energy to power the electronics, therefore only suitable for installations close to power lines or by removable batteries.	0

4.2.2 Monitoring and reporting of battery status

In a system where energy is collected from the environment, the monitoring of the battery status may be made intermittent, synchronous with the measurements, or upon request. As the energy come from harvesting it is important to ensure an efficient management of charging/discharging operations.

The storage system must contain the battery charging circuit, over-voltage and over-current circuit protection, as well as the fuel gauging. The latter has numerous advantages, such as the track of the remaining capacity and the measurement of critical battery pack parameters.

Some types of batteries, in particular the lithium and its derivatives, may not be able to withstand very high temperatures. In those cases other battery types should be used, and a temperature sensor should be added for safety [2].

Rating

Description	Score
Monitoring of battery status synchronous with the measurements or under request.	10
Monitoring of battery status only under request.	5
Not able to monitor battery status.	0

4.2.3 Self-diagnostic

The real-time measurement of the battery parameters and status is the key for an autonomous system, allowing properly management of the system without damage.

The host processor can be responsible to interrogate the battery fuel gauge over a simple one, or two-wire, communications port to acquire the battery information that is important to manage efficiently the system resources and peripherals.

The battery monitoring device can have the following set of registers: voltage, current, remaining capacity, full-charge capacity, temperature.

Rating

Description	Score
Complete set of battery parameters (voltage, current, remaining capacity, full-charge capacity, temperature)	10
Capacity level	5
No sensing ability	0

The battery monitoring device can include an impedance track algorithm that uses the values of current and voltage to calculate the impedance, adjusting then the remaining state-of-charge up or down to the predicted discharge curve. By using the predicted discharge curve, the gauge can accurately calculate the battery pack's remaining operation time.

Charge control and protection are common requirements for a battery powered system. On the other hand, integrating a good fuel gauging system becomes more desirable to properly manage the available power, alerting the user about the operating-time and the life time of the battery [3].

By monitoring the battery status, it is also possible to evaluate indirectly the condition of the transducers used to gather the energy from the environment.

4.2.4 Environmental compatibility

All systems components installed on, or close to the railway shall be in conformity with the requirements of EN 50125-3 (Railway applications. Environmental conditions for equipment. Equipment for signalling and telecommunications).

Rating

Description	Score
EN 50125-3 compliance	10
EN 50125-3 NO compliance	0

4.2.5 Resistance to electromagnetic fields

This subsystem should be suitable for electromagnetically contaminated environments, according to the European regulation.

Rating

Feature	Score
The device works normally on electromagnetic contaminated environments.	10
The device is sensitive to electromagnetic contaminated environment, reducing its performance.	0
The device is not able to work on electromagnetic contaminated environments.	

4.2.6 Mounting simplicity

The energy harvesting equipment should have a very simple mounting procedure, looking for a plug & play approach.

RATING

Description	Score
Plug&Play of energy harvesting device without needing to dismount the sensing node.	10
Plug&Play of energy harvesting device, but after dismounting the sensing node.	5
No Plug&Play	0

4.3 Communications

4.3.1 Fast data transmission

The data transmission from the sensor till data storage shall be rapid. It is desirable that data is accessible in a “back-office” database within 1 hour after collection [4].

RATING

Description	Score
Real-time on near real-time data transmission	10
Data transmitted to the central database within 1 hour after collection.	5
Data transmitted to the central database more than 1 hour after collection.	0

4.3.2 Wireless communication

Wireless communication enables the collection of monitoring data without the need of a physical line. Unlike railway signalling and other critical subsystems which remain linked by physical cables due to safety and security reasons, other railway subsystems such as telecommunications currently use the wireless technology. Wireless Sensor Networks (WSN) are currently used to monitor the condition of civil infrastructures.

RATING

Description	Score
Wireless communication capabilities.	10
Only physical links are possible.	0

4.3.3 Standard interface for wireless

Several standards are currently either ratified or under development by different organizations in the field of WSNs. Standards are used far less in WSN than in other computing systems which make difficult direct communication between different systems. However the selected systems should belong to one of the predominant standards commonly used in WSN communications (ZigBee, 802.15.04 or 6LoWPAN).

Rating

Description	Score
Communication standard ZigBee, 802.15.04 or 6LoWPAN	10
Other communication standard	0

4.3.4 Industrial Ethernet communications interface

Once data has been gathered by sensors and transmitted to the head node or signal cabinet close to the railway track, the data has to be transferred to the head office or maintenance base. This could be done also by wireless technologies, as sensor network will do, but due to the long distances to be covered and the reduced safety of public communication networks, a possible solution is the use of the railway signalling system for this data link, providing that the network allows for the prioritization of traffic so that the safety-critical messages can take priority over monitoring messages. The Industrial Ethernet interface has this capability and this solution can reduce cabling costs and improve access to data.

Rating

Description	Score
Ability to use the signalling system to transmit the data.	10
Not compatible with signaling system.	0

4.3.5 Custom message format for internal communications

A standard file format will be agreed for every message sent or received between the components of the monitoring system. Every sensor and hardware integrated in it should be able to be customized to this standard for transmitting the internal messages.

Rating

Description	Score
Customizable data format.	10
Not customizable data format.	0

4.3.6 Time synchronization

Nodes within a cluster or a network need to compare their readings of complex data that encodes the observation of an event. If the monitoring task is some kind of acoustic emission analysis for example, each sensor has to be able to compare a transient acoustic wave with its neighbours in order to discard data that does not need to be forwarded. It is this in-node and in-cluster data analysis that allows the network to reduce the amount of information that needs to be forwarded to the sink, thus reducing the number of packets sent over the air.

In order to perform this comparison and to localize the damage zone, time synchronization techniques with precision less than 60µs are desirable [5].

Rating

Description	Score
Time synchronization precision below 30 µs	10
Time synchronization precision below 60 µs	5
Time synchronization precision above 60 µs	0

5 MID LEVEL REQUIREMENTS

The mid-level requirements relate to the gathering of data from the infrastructure and the contextual interpretation of this data to provide information on the state or condition of a particular asset. Processing algorithms, running either on localized or centralized processing, are applied to the recorded data in order to provide additional evaluation of the present and / or future condition of an asset.

5.1 DATA AGGREGATION, FUSION AND STORAGE

5.1.1 DATA AGGREGATION AND SIGNAL ANALYSIS

This process of transforming raw signals and data into useful information on asset condition can require a high degree of data processing on what can be very large data sets, for example the machine interpretation of multi-channel, high frequency data, or images or video data. As sensing technologies translate from asset to consumable technologies (i.e. reduce in cost) they will become more prevalent within the rail industry. With this anticipated increase in the use and number of sensors and, in particular, their application on railway infrastructure, processing data into information potentially becomes a significant challenge. One of the key architectural questions is between localized and centralized processing. That is, whether to process data local to the sensors and send only the post-processed events and potentially the supporting data, or to transmit the raw data back to a central repository for retention and / or processing.

A number of factors are significant in the selection of the overall processing architecture. Obviously the data volume is significant, but consideration should also be given to the processing and data communication requirements and how they map into both the localized and centralized architectures. To some degree, there is also a question of the amount of electrical power required for each option – this is of particular significance in light of the discussion of energy harvesting earlier in this document. However, the processing power of modern electronics is ever increasing while the power requirements fall. So it is suggested that in order to minimize the data transfer through the radio module, signal processing and data analysis should ideally be done at the sensor mote as far as possible on the basis that data transmission is likely to be more “power hungry” than local processing.

Towards this end, aggregation functions like MIN, MAX, COUNT; etc. (or more advanced processing) can be used for certain types of data in order to further minimize the amount of transmitted data. Also, while it used to be the case that hardware would be used for complex processes such as filtering and Fast Fourier Transforms (FFT), it is suggested that for modern systems it is generally better to do this digitally, local to the sensor wherever possible.

RATING

Description	Score
Data processing at the sensor node	10
Centralized data processing	0

5.1.2 Time Synchronization

In most monitoring applications, there needs to be an accurate time stamp on data gathered. This is particularly significant when data is being collected across a spatially distributed sensor network. At a general level, this enables patterns developing over time to be assessed, but on a more granular level, there may be a number of sensors being used in combination to assess the condition of a particular asset. In this case, it may well be that data time stamps need to be to a very high level of precision as the event being monitored (i.e. the reaction of a switch tip to the loads imparted by passing wheels, or electrical spikes in a power network) may be transitory and require a high sampling frequency.

One approach increasingly used is to use GPS time stamps for data. These provide consistency over a number of sensor locations but are generally not of sufficiently high precision for transient effects. In this case, a local high precision RTCC is often combined with the GPS timestamp with the former providing the precision and the latter compensating for longer term drift. The cost and power requirements of modern GPS receivers are low, while modern RTCC have extremely low drift characteristics. Regardless of the method used, all data needs to be time stamped with a high degree of confidence, accuracy, and depending on the application, precision.

Rating

Description	Score
RTCC and GPS combined timestamp	10
GPS timestamp	5
No timestamp	0

5.1.3 Spatial synchronization (only embarked sensors)

In general, spatial synchronisation tends to be more of a concern for train-borne condition monitoring systems, particularly those where systems mounted on a vehicle are used to monitor the infrastructure. There are several techniques to gather localization data, such as GPS, odometer or signalling, however the accuracy of localisation is usually improved by the combination of them.

RATING

Description	Score
Combined GPS, odometer and signalling system for data localisation	10
Only one system available for data localisation	5
No system for data localisation	0

5.1.4 DATA SECURITY & INTEGRITY

Regardless of whether data processing is done at the sensor end or in a centralised location, data security and integrity is an important issue. Modern data management protocols include capacity for data provenance; this is particularly useful when data is exchanged between multiple systems. On a localised level, the primary concern is more of data being corrupted during communication than concerns over a malicious attack, but of course data may also be of a commercially sensitive nature. It is likely necessary to encrypt all data transmission to moderns secure standards, and to include data verification routines with transmission systems. This tends to be included as a standard feature of modern communication systems, but is none-the-less an important requirement. Recent work has involved mapping the communications infrastructure in the context of the railway environment in order to develop a better understanding of the data transmission and encoding requirements for robust systems.

RATING

Description	Score
Encryption and verification routines of data available	10
Only encryption of data is available	5
No encryption and verification routines are available	0

5.1.5 DATA ANALYSIS SPEED

With the exception of maintenance related issues and those caused by other external stimuli, changes to the infrastructure tend to be gradual, relating primarily to wear and deterioration over time rather than instantaneous failures. The intention of condition monitoring prognosis is to monitor these trends over time and predict when some form of intervention will be required. For usual infrastructure data, it is suggested that it should be possible to process and transmit data within a matter of minutes of a measurement being taken. But as a general guide, the raw data should be processed, transmitted, fused and analysed within 24 hours of a measurement being taken [6]. This will allow the Asset Management tool to deal with updated information which is a key factor for the planning of corrective/emergency maintenance tasks.

Depending on the measurement(s) being taken, there should also be an option for an emergency flag to be raised whereby an alarm is raised immediately upon receipt at the central location / back-office.

RATING

Description	Score
Data analysed and condition indicators available within 12 hours after collection.	10
Data analysed and condition indicators available within 24 hours after collection.	5
Data analysed and condition indicators available over 24 hours after collection.	0

5.1.6 Big data capabilities

The power of modern computing allows that handling of enormous datasets, running to Gigabytes or Terabytes of data. In contrast to the general requirement to process data locally into information on the status of an asset or component, it is now possible to transmit raw data to a central processing centre. This gives a much greater scope and flexibility to use alternative analysis methods, perhaps looking for patterns in the data that were not originally envisaged when the sensors were installed. Such mechanisms also provide the capacity for greater analysis to be carried out over geographically separated assets. The “Big Data” mechanism also provides processing support for disparate datasets, i.e. those containing signals which are at face value unrelated. The processing requirements for big data system are, however, still substantial and often may still qualify as prohibitive even with modern computational capacity.

RATING

Description	Score
Big data capabilities	10
No big data capabilities	0

5.1.7 Cloud computing

Modern ICT techniques such as cloud computing could be applied to real-time data processing of measurements. Cloud processing is generally only limited by the internal communications infrastructure and is therefore significantly more powerful than a localized (distributed) processing alternative. This technological step is necessary linked to the data communication as the cloud architecture provides alternative processing capability with the tradeoff that the data must be transmitted to the off-site processing elements

A further challenge is the development of robust and proven algorithms suitable for running on the cloud computing platform. This can take a great deal of effort, particularly proving the robustness of more complex systems is a concern, particularly the need to guarantee that developing issues will be reliably detected whilst avoiding false positives and alerts. Other challenges include the need to avoid "information overload" and the need to reduce overall power consumption as the desire to use energy harvesting technology limits the power available for data collection, processing and communications.

RATING

Description	Score
Cloud computing provided with complex analysis algorithms is available	10
Cloud computing is available, but only basic calculations are possible	5
No cloud computing capabilities	0

5.2 FAULT DETECTION (DEFECT RECOGNITION)

5.2.1 REAL-TIME DATA PROCESSING

Sudden defects in rail infrastructure are usually detected by train drivers which inform the maintenance division. This process is usually reasonably fast with real time, or near real time, driver reports being actioned immediately for further review on a set timescale. However current European railway industry is shifting to open market where several operators use the same infrastructure owned by the infrastructure manager. This change will make difficult the involvement of train drivers in detecting and / or reporting faults. By hence, a more consistent solution, whereby sudden defects shall be detected by the infrastructure and informed to the maintenance manager as fast as possible, has to be developed.

RATING

Description	Score
Sudden defects are detected by the monitoring systems and the rail operator is advised within 10 minutes after it occurs.	10
Sudden defects are detected by the monitoring systems and the rail operator is advised within 1 hour after it occurs.	5
Sudden defects can only be detected once a day, after data processing.	0

5.2.2 Custom fault detection rules at system level

Some defects cannot be detected at component level because it depends on the combined measurement of several sensor nodes. Alternatively, a localised interpretation of a signal may be altered if, for example, all the nodes in one area reported the same effect. In this case it would be likely that some local phenomenon was impacting on the processing. In this context, a higher level (re-)interpretation of the recorded data is required. Therefore, the detection of such kind of defects shall be done at an additional analysis stage.

RATING

Description	Score
Additional analysis stage to detect/discard faults at system level	10
No ability to detect/discard faults at system level	0

5.2.3 Adaptable methods and tools for data analysis

The system can be provided with an initial catalogue of defects, such as UIC-712, although new defect patterns shall be added to the database when they are detected and classified. Processing algorithms would need to be adaptable in order to accommodate such changes in the catalogue. This has implications for the architecture used: centralised or cloud based processing systems would be comparably easy to update and could make use of a modular processing architecture. Distributed or localised processing systems would need to have capacity to “roll out” processing updates over a network. This would have implications for communications protocols, interface specifications, communications bandwidth and architectures.

RATING

Description	Score
The detection algorithms are able to evolve and be adapted to new types of data	10
The detection algorithms are not able to evolve and be adapted to new types of data	0

5.2.4 Extreme Learning Machine approach

This requirement embodies the ability of the system to perform a neural-based classification scheme for detecting the presence and location of defects. For the sake of lessening the computational complexity and in favour of a quick response of the overall system, the adoption of the so-called Extreme Learning Machines (ELMs) is considered as an advantage. This methodology is a specific subclass of "generalized" single-hidden layer feed-forward networks (SLFNs) which has gained momentum in the last years due to its ease of use, improved generalization performance and faster learning speed with respect to other classification counterparts existing in the literature (e.g. SVM or conventional neural networks).

When using these approaches, particular consideration must be given to the presentation of such systems to existing staff and maintenance crews. Often these processing mechanisms are non-transparent or have limited traceability and thus it can be difficult to obtain sufficient buy-in from the staff they are intended to benefit.

RATING

Description	Score
Use of Extreme Learning Machine techniques for fault detection	10
Not use of Extreme Learning Machine techniques for fault detection	0

5.3 Diagnosis (Evaluation algorithms)

5.3.1 Instant access to historical data

The most basic of monitoring systems are used primarily as date recorders in order to facilitate event playback. This is often of particular use in post event analysis, either following obvious significant incidents or in order to verify reported / suspected occurrences. In these cases, the connectivity and usability of the systems are of particular importance. Alternatively, longer term historical and trend data can be useful to feed the algorithms for prediction of asset degradation, as well as an important support to decision making. This information should be stored with the required security and reliability level, and it should available permanently from every maintenance base Large databases, either centralized or distributed, seem to be suitable to store the huge amount of data coming from the monitoring system, particularly from acoustic or visual sensors.

RATING

Description	Score
Evaluation algorithms can access to historical data	10
No access to historical data	0

5.3.2 DETERMINISTIC APPROACH TO DIAGNOSIS

On a more advanced level, condition monitoring systems make use of data recorded from a system to infer things about the overall system health. Fault detection systems use these inferences to identify early stage incipient faults and thus can be used to target maintenance prior to failures. Diagnosis systems extend this process to identify from the data the particular nature of the fault and thus more precisely direct the required maintenance work. Track degradation is a consequence of defects at component level. For instance, loss of tight in fastenings could derive in excess of gauge. It is expected that evaluation algorithms could perform a retro-analysis to infer the origin of the defect and not its consequence. This will make possible the prediction of degradation trends on the basis of component-related degradation laws.

RATING

Description	Score
Ability to derive cause-effect relationships and use them to anticipate faults occurrence.	10
Only basic rules to derive system failures from degradation trends at component level	0

5.4 PROGNOSIS (DEGRADATION ALGORITHMS)

The logical extension from event reporting, through fault detection and fault diagnosis is fault prognosis. Broadly, this means that the diagnosis systems put performance parameters on the components identified to be failing in order to identify and quantify the failure process. By doing this, it is possible (either through modeling or trend analysis) that the systems can evaluate and thus predict the future failure schedule of the component in order to allow greater optimization of targeted maintenance.

5.4.1 ADVANCED MODELLING FOR TRACK DEGRADATION

There are several models for predicting asset degradation, such as **symbolic models**, based on empirical and rule-based relationships, **data-driven models**, which approach is derived directly from routinely gathered data, and **physical models**, applicable in case of well-known degradation processes. During the last years, a new type of mixed models has arisen in the scientific spheres: the **hybrid models**. These models use the power of previous approaches and fill the gap among them with advanced algorithms, which allows more accurate and robust prediction of defect degradation.

RATING

Description	Score
Degradation algorithms are based on advanced hybrid models.	10
Degradation algorithms are based on physical or data-driven models.	5
Degradation algorithms are rule-based (symbolic models).	0

5.4.2 INSTANT ACCESS TO CUMULATIVE TRACK LOADS

Cumulative load is the main variable in defect degradation laws. Using a "big data" processing approach, the predictive tool shall be able to access to the Traffic Management Systems and look for timetables (passengers and freight traffic) in order to use the expected cumulative traffic load as an input to the algorithms. By incorporating the loading (and thus wear) elements into the model based systems it should be possible to improve the interpretation of data for diagnosis and also prognosis processes.

RATING

Description	Score
The system is able to obtain inputs from the Traffic Management Systems (cumulative track loads)	10
The system is not able to obtain inputs from the Traffic Management Systems (cumulative track loads)	0

5.4.3 AUTO-ADJUSTING OF DEGRADATION MODELS

At present, moderators for track or asset wear are manually incorporated into model based diagnosis and prognosis systems, largely as a post process modifier. Generally, the interpretation of the automated tools' results is subject to "sanity checks" from engineers. For a better understanding of the effects of wear on the fault degradation models it will be possible to incorporate the information into the processing at an earlier stage. The predictions shall be automatically adjusted to the observed data.

RATING

Description	Score
Predictions are dynamically updated and adjusted to the observed data.	10
Parameters of degradation algorithms can only be adjusted manually.	5
Degradation models are fixed and cannot be adjusted to the observed data.	0

5.4.4 DEFECT PREDICTION

Previous requirements deal with the prediction of degradation of already detected and existing failures. A further step deals with the estimation of the probability of new and undetected failures (number and distribution in time) using RAMS techniques. In part, this process would be based on natural wear quantification combined with statistical analysis of fault prediction with component age / life cycle.

RATING

Description	Score
New defects can be predicted by RAMS simulations.	10
New defects can be predicted on simple probabilistic basis.	5
New defects cannot be predicted.	0

5.4.5 Report of stochastic information to the decision support system

Due to the high reliability of railway infrastructures and the extremely large life cycle of its assets compared with other industries, a probabilistic approach for the integration of failure modes is necessary for the optimization of maintenance planning and for the estimation and assessment of the network infrastructure cost.

Modern optimization algorithms built on Decision Support Systems are fed by stochastic information, rather than simple estimators for mean and variance of degradation parameters.

Rating

Description	Score
The system provides the decision support with probabilistic information about asset condition.	10
Deterministic information is sent to the decision support tools.	5
Only basic statistics (average, standard deviation) are provided by the decisions support.	0

6 HIGH LEVEL REQUIREMENTS

The upper layer of the monitoring system deal with the user interfaces and the integration/communication with existing databases and information systems, such as the Maintenance Management System or the Traffic Management System. The requirements at this level are provided by the Infrastructure Managers and Operators, in particular the asset manager responsible.

There is a lot of previous research effort done in this area. FP6 projects such as InteGRail [7] and Innotrack [8], where the most relevant European Infrastructure Managers participated, carried out questionnaires on the high level requirements for new information systems to be developed within those projects.

On the other hand, the UIC published in 2010 a guideline for the application of asset management in railway infrastructure organisations [9], which contains numerous references to the requirements that every railway system, such as the monitoring system, shall accomplish to be properly integrated in this kind of management tools. In the same year, the UIC working group on track condition monitoring asked to 16 Infrastructure Managers about current monitoring strategies and best practices on the integration of the gathered data in information systems. One of the main results mentioned in the synthesis report [10] is the lack of standardization in data management and information exchange.

The following subsections describe and quantify the importance of these high level requirements on the monitoring systems.

6.1 GEOGRAPHICALLY REFERENCED DATA

The data should be referenced to particular assets within the railway network. Moreover, a geographical reference is also useful to feed man-machine interfaces usually built in asset management software. But the data should be referenced not only geographically, and rather from the network point of view, with direct linkage to the infrastructure description data (network nodes, edges, and their elements and attributes).

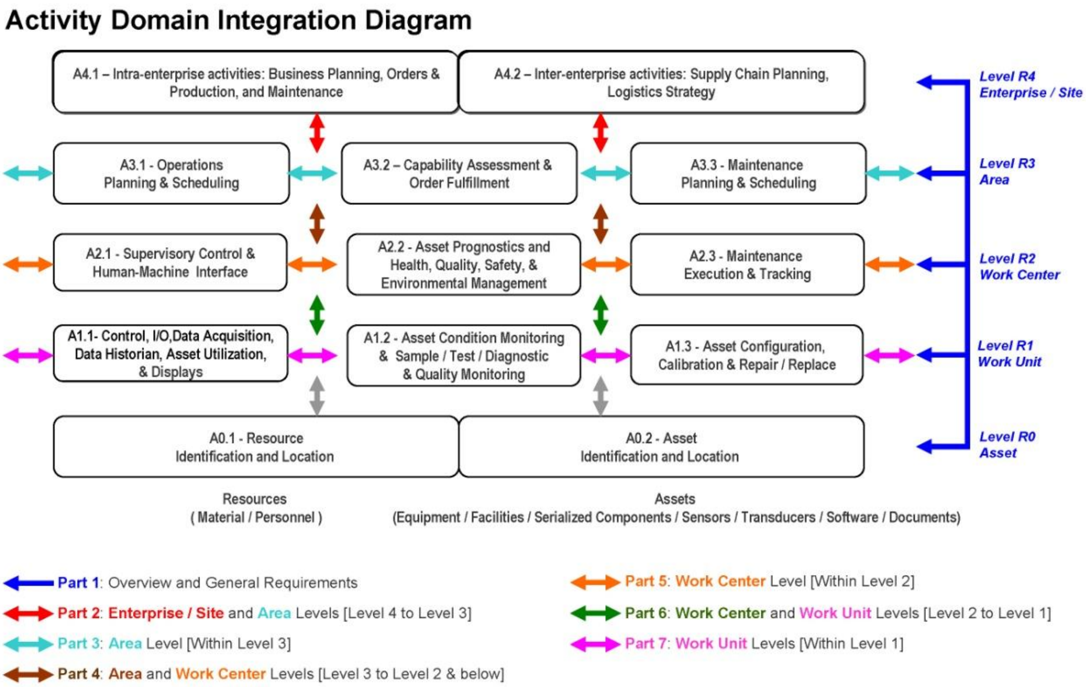
Existing standards, such as XML format, shall be used for data transfer and presentation. This will reduce the development and integration time.

Description	Score
Localization layer linked to the measurement data and able to deal with several GIS formats (shape, kml, etc.)	10
Geographic references embedded in the measurement data (XML format)	5
Measurement data not geographically referenced	0

6.2 INTEROPERABILITY WITH OTHER RAILWAY SUBSYSTEMS

Concerning communication with external systems, a common file format shall be established. This will allow the integration of monitoring systems with information systems currently owned by the Infrastructure Managers, such as the Asset Management tools, Computerized Maintenance Management Systems (CMMS) and Enterprise Resource Planners (ERP).

The XML file format is in widespread use and is readily compatible with web-based applications, it make sense to select this standard as a minimum requirement for external communications. More advanced are the procedures for information exchanges proposed by the ISO 18435-1:2009 [11] . It is expected that in the following years, every information system belonging to the railway environment is able to be integrated according to this standard.



RATING

Description	Score
Fully compliance of ISO 18435	10
XML format for external communications	5
Non-standard format for external communications	0

6.3 Ontology based standard Railway Data Model

Previous standard for interoperability is open to any industrial system. In order to develop a holistic, coherent information system in the railway domain, it is necessary to keep a common ontology in all the interacting subsystems. Ontology in a specification of a conceptualization, a collection of structured and organized concepts and assertions that describe knowledge in selected observable domains of interest. The Rail Domain Ontology provides a generic solution for information exchange. It is proposed to be particularly appropriate in an environment where there are numerous heterogeneous information sources as rail domain.

RATING

Description	Score
Includes a common rail domain ontology	10
Not includes a common rail domain ontology	0

6.4 Standard protocol to access external databases

In order to properly detect the fault and its root cause in every situation, the monitoring system shall be able to gather information from other external systems (e.g. a weather station or an emergency information system) to integrate situation-dependent information such as temperature, wind speed, rain, floods, earthquakes, etc. in the interpretation process [12] . For seamlessly exchanging such information, the Foundation of Intelligent Physical Agents (FIPA) has proposed the Unified Modelling Language (UML). This standard has been recently adopted by the ISO 13374-2:2007 [13] as the external communications protocol for condition monitoring systems.

RATING

Description	Score
Use of protocols based on Unified Modelling Language (UML)	10
Use of others compatibles protocols	5
Non-use of standardized languages for interacting with other external information systems	0

6.5 Web-based storing and application systems

The allocation of monitoring data, algorithms and communication interfaces in a web service is a state-of-the-art solution in all industrial sectors. Once security and privacy issues are solved, the web services represent a highly flexible way to access to asset information from any management system (maintenance, operation, financial department, etc.). The key benefit is a gain of performance compared to centralized management since lower-level data interpretation can already be initially locally and interpreted in parallel on different information hierarchy levels. This additionally allows communication less information – the local reasoning results – to subsequent higher-level reasoning nodes for further processing. This approach also supports means for data and process abstraction, which enables information to be disclosed limited to authorised information processing partners [12].

Rating

Description	Score
Web-server based system allocating data and interpretation tools	10
Web-server based system allocating only data, but interpretation tools kept at local level	5
Non-use of web-server	0

7 EVALUATION FRAMEWORK

This chapter sets out the evaluation framework to objectively compare different monitoring systems under the same particular working circumstances. The factors described in previous subsections are weighted within each group according to their importance. In this deliverable, this weight has been considered constant so that every factor is of equal importance. As result, there is a unique number representing the compliance of these requirements (the technical score).

But the selected system shall be also affordable, which is one of the general objectives of the Capacity4Rail project, so it is necessary to consider also its Life Cycle Cost. In the absence of a detailed LCC analysis, the evaluation framework only considers the Total Cost, which has been built on the following assumptions:

- Different unitary costs are considered at component (cost per sensing node) and system levels (cost per monitored network)
- It is always possible to figure out actual costs
- The cost can be separated into: Acquisition, installation, maintenance and decommissioning
- No operation costs are considered
- No discount rates are considered (valid for comparison purposes)
- The life span of the system is about 10 years

Once evaluated, both the technical score and the cost are ranked independently so that the technical and cost performance can be assessed separately.

After that, the best value option is calculated by dividing the total technical score for each option by the appropriate cost and multiplying by 100. The highest “value rating” identifies the best value option for the cost being considered.

$$Value\ rating\ = \frac{Technical\ score}{Total\ Cost} \cdot 100$$

Finally, the evaluation of low level, mid level and high level requirements are put together in chart and bar diagrams in order to have a general view of the different monitoring systems and take the final decision. The compatibility among subsystems is out of the scope of this deliverable, so the user shall discard these options manually.

Following, the spreadsheets developed are shown including a hypothetical monitoring system. These tables will be filled with real data on next tasks within this Work Package, where the relevant technologies available in the market shall be assessed.

EVALUATION FRAMEWORK FOR LOW LEVEL REQUIREMENTS

SENSOR NETWORK CONFIG.	SENSORS																								
	Ref	Description	Automated data collection	Detection of incipient faults	Event localization	Weak up under event	Different time for sensing/sending	Scalability	Environmental compatibility	Data collection at line speed	Different measurement modes	Custom reporting of parameters	Custom fault detection rules	Custom submision rate of measurements	Self-diagnostic	Long term stability	Long term robustness and reliability	Calibration	Geometrical compatibility	Compatibility with track maintenance	High availability on component level	High availability on sensor node	Resistance to electromagnetic fields	Mounting simplicity	**SENSOR SCORE**
	WEIGHT		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	
1	S1	Inclinometer Quest R1	10	10	10	10	5	5	10	0	0	5	5	5	0	5	10	5	10	10	0	5	10	5	**6,1**
	S2	Distancemeter Paralax W2000	10	5	10	10	5	5	10	0	0	0	10	5	0	0	10	5	5	10	0	5	10	5	**5,5**
	S3	Accelerometer MEMS S200	10	5	0	5	5	0	10	0	10	5	0	5	0	0	0	0	10	10	0	5	10	0	**4,1**
2	S2	Distancemeter Paralax W2000	10	5	10	10	5	5	10	0	0	0	10	5	0	0	10	5	5	10	0	5	10	5	**5,5**
	S4																								
3	S2	Distancemeter Paralax W2000	10	5	10	10	5	5	10	0	0	0	10	5	0	0	10	5	5	10	0	5	10	5	**5,5**
	S3	Accelerometer MEMS S200	10	5	0	5	5	0	10	0	10	5	0	5	0	0	0	0	10	10	0	5	10	0	**4,1**
	S4	Strain gauge HBM U10	5	0	10	0	10	10	10	0	10	10	10	0	0	0	0	5	10	5	10	10	10	5	**5,9**

SENSOR NETWORK CONFIG.	ENERGY HARVESTING								
	Ref	Description	Suitability for installation at different sites	Monitoring and reporting of battery status	Self-diagnostic	Environmental compatiblity	Resistance to electromagnetic fields	Mounting simplicity	**ENERGY HARVESTING SCORE**
			17%	17%	17%	17%	17%	17%	
1	E1	Battery 2000mAh	0	10	10	10	5	10	**7,5**
	E2	Photovoltaic accumulating	5	0	5	10	10	0	**5,0**
2	E1	Battery 2000mAh	0	10	10	10	5	10	**7,5**
	E4	Piezoelectric accumulating	5	0	5	10	10	0	**5,0**
3	E3	Battery 5000mAh	0	10	10	10	5	5	**6,7**
	E4	Piezoelectric accumulating	5	0	5	10	10	0	**5,0**

SENSOR NETWORK CONFIG.	COMMUNICATIONS									ATTRIBUTES			COST PER SENSOR NETWORK (€)							VALUE ANALYSI	
	Ref	Description	Fast data transmission	Wireless communication	Standard interface for wireless	Industrial Ethernet communication	Custom message format	Time syncronization	**COMMUNICATION SCORE**	TECHNICAL SCORE	TECHNICAL RANKING	TECHNICAL INCREASE ON LOWEST	ACQUSITION COST	INSTALLATION COST	MAINTENANCE COST (PER YEAR)	DECOMMISSIONING COST	TOTAL COST (10 YEARS)	COST RANKING	COST INCREASE ON LOWEST	**VALUE RATING (TECHNICAL SCORE / COST)**	**VALUE RANKING**
			17%	17%	17%	17%	17%	17%													
1	C1	Antenna type 1	10	10	10	0	10	10	**8,3**	19,4	2	3%	200,0	50,0	20,0	10,0	460,0	3	67%	**4,2**	**3**
	C2	Protocol A	5	10	10	10	0	10	**7,5**												
2	C3	Antenna type 2	5	10	10	0	10	10	**7,5**	19,6	1	4%	100,0	20,0	15,0	5,0	275,0	1	0%	**7,1**	**1**
	C2	Protocol B	10	10	10	0	10	10	**8,3**												
3	C3	Antenna type 2	5	10	10	0	10	10	**7,5**	18,9	3	0%	200,0	60,0	10,0	10,0	370,0	2	35%	**5,1**	**2**
	C2	Protocol B	10	10	10	0	10	10	**8,3**												

In this example, some components are repeated in different configurations. It can be observed how “Configuration 2” has the highest technical score and the lowest cost, so its value rating is much higher than other options.

EVALUATION FRAMEWORK FOR MID LEVEL REQUIREMENTS

PROCESSING ARCHITECTURE CONFIG.	DATA AGGREGATION, FUSION AND STORAGE: Ref Description	Data aggregation and signal analysis	Time synchronization	Spatial synchronization	Data security & integrity	Data analysis speed	Big data capabilities	Cloud computing	**DATA MANAGEMENT SCORE**
	WEIGHT	14%	14%	14%	14%	14%	14%	14%	
1	Proccessing node 1	10	10	5	5	10	0	0	**5,7**
2	Proccessing node 2	0	10	5	5	10	0	5	**5,0**
3	Proccessing node 3	0	5	10	0	10	0	5	**4,3**

PROCESSING ARCHITECTURE CONFIG.	FAULT DETECTION ALGORITHMS: Ref Description	Real-time data processing	Custom fault detection rules at system level	Adaptable methods and tools	Extreme learning machine approach	**FAULT DETECTION SCORE**
		25%	25%	25%	25%	
1	Proccessing node 1	5	10	10	10	**8,8**
2	Proccessing node 2	10	10	10	0	**7,5**
3	Proccessing node 3	0	10	10	0	**5,0**

PROCESSING ARCHITECTURE CONFIG.	EVALUATION ALGORTHIMS: Ref Description	Instant access to historical data	Deterministic approach to diagnosis	**DIAGNOSIS SCORE**
		50%	50%	
1	Proccessing node 1	10	10	**10,0**
2	Proccessing node 2	10	10	**10,0**
3	Proccessing node 3	10	10	**10,0**

PROCESSING ARCHITECTURE CONFIG.	PREDICTIVE ALGORITHMS: Ref Description	Advanced modelling for track degradation	Instant access to cumulative track loads	Auto-adjusting of degradation models	Defect prediction	Report of stochastic information to DSS	**PROGNOSIS SCORE**
		20%	20%	20%	20%	20%	
1		10	10	5	5	0	**6,0**
2		5	10	5	0	0	**4,0**
3		5	0	0	0	0	**1,0**

PROCESSING ARCHITECTURE CONFIG.	ATTRIBUTES: TECHNICAL SCORE	TECHNICAL RANKING	TECHNICAL INCREASE ON LOWEST	COST OF THE SYSTEM FOR DATA ANALYTICS (€): ACQUSITION COST	INSTALLATION COST	MAINTENANCE COST (PER YEAR)	DECOMMISSIONING COST	TOTAL COST (10 YEARS)	COST RANKING	COST INCREASE ON LOWEST	VALUE ANALYSI: **VALUE RATING (TECHNICAL SCORE / COST)**	**VALUE RANKING**
1	24,5	1	27%	500,0	60,0	10,0	5,0	665,0	3	50%	**3,7**	**3**
2	22,5	2	17%	400,0	60,0	10,0	5,0	565,0	2	28%	**4,0**	**2**
3	19,3	3	0%	350,0	40,0	5,0	2,0	442,0	1	0%	**4,4**	**1**

In previous table, the “Processing node 1” is the most convenient from the technical point of view, but its high cost pushes it into the background and the “Processing node 3” results the preferable option, in spite of its lower compliance of technical requirements.

EVALUATION FRAMEWORK FOR HIGH LEVEL REQUIREMENTS

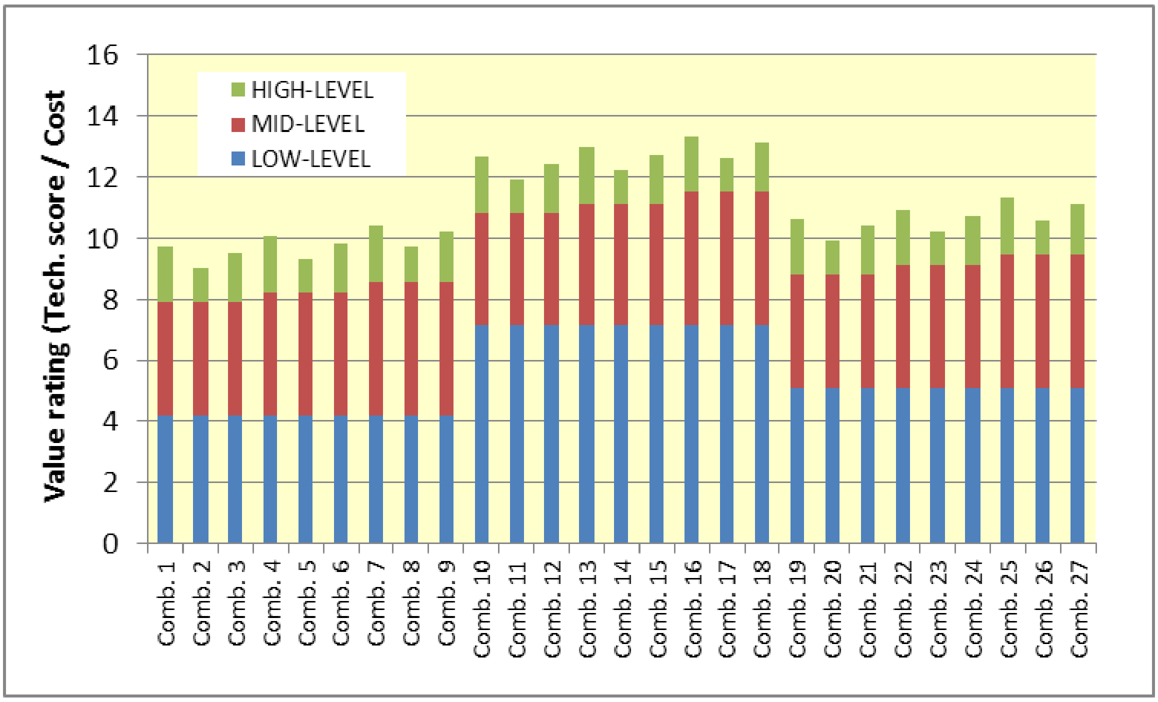
	INTEGRATION							ATTRIBUTES			COST OF THE SYSTEM FOR DATA ANALYTICS (€)							VALUE ANALYSI	
INTEGRATION GATEWAY CONFIG.	Ref Description	Geographically referenced data	Interoperability with other railway subsystems	Ontology based standard Railway Data Model	Standard protocol to access to external databases	Web-based storing and application system	**INTEGRATION SCORE**	TECHNICAL SCORE	TECHNICAL RANKING	TECHNICAL INCREASE ON LOWEST	ACQUSITION COST	INSTALLATION COST	MAINTENANCE COST (PER YEAR)	DECOMMISSIONING COST	TOTAL COST (10 YEARS)	COST RANKING	COST INCREASE ON LOWEST	**VALUE RATING (TECHNICAL SCORE / COST)**	**VALUE RANKING**
	WEIGHT	20%	20%	20%	20%	20%													
1	Integration gateway 1	10	5	10	5	10	**8,0**	8,0	1	167%	150,0	30,0	25,0	5,0	435,0	3	135%	**1,8**	**1**
2	Integration gateway 2	0	5	0	5	10	**4,0**	4,0	2	33%	125,0	30,0	20,0	5,0	360,0	2	95%	**1,1**	**3**
3	Integration gateway 3	5	5	0	5	0	**3,0**	3,0	3	0%	70,0	10,0	10,0	5,0	185,0	1	0%	**1,6**	**2**

All the high level requirements are related to the integration with third party software and external databases. In previous example, it is supposed that a standard integration gateway is developed and used on existing railway organisations. However, it is usual to build tailor-made solutions which overcome all the interoperability and communication issues. In this case, the “Integration gateway 1” accomplishes much better the technical requirements and has also a competitive cost, so that this is the best solution.

RESULTS

Once evaluated, the different components at high, mid and low level shall be combined to build the monitoring system. Obviously, not all the combinations among subsystems are possible. The user of this methodology must discard the incompatible configurations.

Next figure shows that in previous examples the low-level components (sensors, energy harvesting and communication) have major impact on the global value rating. The optimal combination shall be selected among Comb.10 and Comb.18, where the configuration 2 of the sensor network had the highest score.



After discarding the incompatible solutions, there will be only 2 or 3 monitoring systems meeting the identified requirements and thus the general goals of the project.

8 CONCLUSIONS

The functional and technical requirements have been identified for each one of the monitoring components, at high, mid and low level. A proposed rating table is given to facilitate the assessment of the features of the components under each criterion.

The evaluation framework is built considering both the technical and cost factors, so that the value rating obtained helps to select the subsystems that better meet the identified requirements at the lowest cost.

The results of the evaluation at high, mid and low level are put together to identify a group of good solutions from the technical and economical point of view. It is envisaged that a second evaluation loop shall be done to select the optimal monitoring system among the 5-6 alternatives identified in the previous step. To this end, more accurate technical and costs assessment shall be entered in the spreadsheets.

It is worth to mention that this evaluation framework is only an initial outline to be used and debugged during the selection of technologies that will be carried out in later tasks within this WP. After that selection process, it is foreseen to submit a second release of this deliverable with a final list of requirements, more detailed rating tables for each technology and an improved evaluation framework.

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