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Deliverable D 2.4
Requirements and Architecture specification

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1. Executive Summary

The main objective of the LOCATE project is to replace, when it decreases the cost or improves the reliability, availability, or maintainability of locomotives at a constant or lower level of risk, the preventive conditional and scheduled maintenance of mechanical parts of the bogie by predictive maintenance to:

- Ensure safety by having parts of the subsystem under continuous surveillance, thereby replacing planned inspections.
- Increase the availability of the locomotives by avoiding unnecessary controls or inspections done by the driver or the maintenance team performing, such as:
    - Light maintenance controls between 2 commercial trains
    - Heavier annual inspections
    - Replacement of subsystems in good health which are safe for continued operation.
- Reduce the number of unforeseen defects/incidents to increase reliability.
- Schedule interventions before the problem influences operations by identifying the warning signs of failures (data) and the corresponding degradation rates.
- Consider the constraints of the:
    - drivers
    - fleet management
    - workshop management
    - people in the workshop
- Keep under control the interfaces with the infrastructure

The following tools and methodologies will be implemented:

- Identifying faulty components by means of vibration analysis based on data collected with sensors fitted to bogie sub-systems. The data collected is then processed to make possible reliable maintenance decisions (time before withdrawal from service and conditions for return to operation)
- Supporting maintenance scheduling and integrating maintenance operations tasks into daily services, while ensuring appropriate inventory control of stock and spare parts and assigning maintenance crew/technicians according to their skills/competences

Therefore, we shall modify the maintenance framework and intervention criteria for the demonstrator locomotive. Proof must be provided that the safety level is preserved or improved. We will make use of established methods, where possible, already used by several railway operators inside Europe as proposed when implementing the Entities in Charge of Maintenance.

This document presents the feedback for state of art and other Shift2rail projects, and then describes requirements for the LOCATE project implementation with instrumentation associated for the defined use case.

General architecture will be:

- OBU inside the cabin
- Conditioning system outside the cabin

- Analog sensors on the sub systems
- Communication of OBU with Centralized System

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
CBM	Condition Based Maintenance
MVB	Multifunction Vehicle Bus
OBU	On Board Unit
DAQ	Data Acquisition System

3. Background

The present document constitutes the Deliverable D2.4 “Requirement and Architecture specification” as part of the WP2 – Requirements and Specifications.

It does not contribute any TD/WA.

The assumptions made in this document are based on the work of previous tasks of WP2 – Requirements and Specifications, namely the results provided in deliverables D2.1 Use Case Description and D2.3 FMECA Analysis and D4.1 available models assessment.

4. Objective/Aim

The aim of the LOCATE project is to provide the methods and tools by which every Entity in Charge of its Maintenance (ECM) to implement predictive maintenance of bogie, which is one of safety-critical component in a rail vehicle, to:

- Ensure safety: The parts concerned are continuously under surveillance.
- Increase availability and reduce cost by avoiding unnecessary controls. Most checks do not result in repair or replacement. The data collected makes a continuous improvement of the maintenance process easier to implement.
- Increase reliability: Interventions are made before any problem in operation.
- Without impact on maintainability: The implementation of surveillance equipment will be done under the control of the people doing the maintenance.

The main objective of LOCATE project is to replace as necessary as possible the preventive conditional or scheduled maintenance of mechanical parts of the bogie by predictive maintenance. It is expected that a condition –based monitoring maintenance program will:

- Increase availability (concerns only the time to work on the bogie). 30%
- Decrease of the costs (only the maintenance costs of the bogie) 20%
- Increase of the reliability (of the bogies and the components linked) 60% (incidents per unit of route)

LOCATE will ensure the above primary S2R performance indicators are met through two key areas; firstly, a reduction in life cycle costs (LCC) and, secondly, an increase reliability, availability, maintainability with an assurance that the new regime with have safety levels remain the same show improvement (RAMS).

It is expected that the benefits will be demonstrated in the LOCATE use case through the reduction of operational costs from condition monitoring and reduction in maintenance costs from optimised maintenance procedures for specific selected components through the use of predictive models derived from digital representation of components and measured condition data.

LOCATE will realise an increase in in the reliability of the freight locomotive by the early warning in the running condition of the vehicle detected from sensors fitted on the vehicle. Damage from unforeseen failures will be reduced by monitoring and the definition of condition thresholds specified by simulated fault analysis from the vehicle reference behaviour derived through dynamic modelling of components. Mean time

Predictive models from data generated from digital representations and data gathered through condition monitoring will allow assets to be effectively managed by a computerised asset management system.

Outputs from the predictive models will be used to develop interfaces that could link to a dedicated computerised maintenance management system (CMMS).

The LOCATE will develop tools and methods:

- To identify the failures in the bogies, primary and secondary suspensions, wheels, electric traction motor, or transmission. LOCATE development will be able to anticipate these failures from several days to several weeks.
- To do pre-operational and operational planning using the data produced.

4.1. Deliverable Objectives

The goal of the "Task 2.5 - Architecture Specification" is to define an overall and detailed System Architecture capable of implementing the use case specified, addressing the associated requirements. This Architecture will specify the functions and type of input/output needed to be implemented for the acquisition, collection, processing, and storage of data.

Thanks to deliverable D2.1, the use cases are defined and the subsystems to monitor are the following:

- Wheelset subsystems
- Axlebox
- Bogie Frame
- Brake System
- Suspension system / elements
- Electric Traction Motor

Deliverable D2.3 conducts a Failure Modes, Effects, and Criticality Analysis (FMECA) on the defined use cases of D2.1. The components identified as critical were the following:

1. Brake System,
2. Wheelset components,
3. Electric Traction Module,
4. Axle Box,
5. Suspension System,
6. Bogie frame.

The particularity of the project is to mix the signal analysis of on-board measurements with model-based approach developed in WP4.
Deliverable D.4.1 untitled "available models' assessment" presents the adopted strategy in regard

to the identified critical components and the state of the art in terms of model-based approach for Condition Based Monitoring.
Major conclusion of the D4.1. is that a model-based approach on the following subsystems will be developed to go from default identification to fatigue /degradation indicators:

- Wheelset axle crack
- Bogie frame crack
- Degradation of suspension elements

Axle Box, Brakes and Electric Engine, will not have digital twins developed. Like is stated in D4.1, Brakes are analysed by direct parameters, Axle Box will use MAXBE project results regarding Models, and Electric Engine, although it will have implemented monitoring sensors, it will not have any developments on Digital Twins or Computational Models.

This document has been prepared to provide the architecture and requirements of the monitoring system to install on the locomotive and of the remaining systems and tools, to implement a CBM program.

4.2. Global approach on measurement

The measurement campaigns will be divided in two main parts:

Part 1: Measurement for diagnosis and digital twin set-up

It consists of a first short duration measurement campaign (one week) to analyse the dynamic behaviour of the locomotive and have a global overview of the track condition. It will also help to evaluate the best sensors and set-up for the long term's measurement campaign (part 2).

At this stage, the monitoring system will be implemented in an offline approach, where the raw data will be recorded and latter download for processing and studying.

Part 2: Measurement for CBM demonstration

It is a long terms measurement campaign (several months) that will be correlated with the digital twins to demonstrates the approach implemented in LOCATE project. During this stage it will be possible to determine the minimal datasets and final minimal specifications to implement a predictive maintenance program.

At this stage, the monitoring system will already be online, communicating the minimal datasets to a central database, and continuously evaluating thresholds.

5. Feedback for state of art and other Shift2rail projects

5.1. General

Some Shift2rail projects (RUN2RAIL, IMPACT, INNOWAG) have a work package dedicated to technologies for wagon monitoring systems or description of the CBM data structures or architecture (see references [1] to [8]).
A similar architecture is presented in all these shift2rail projects and most of the new generation of locomotive have such equipment and it exists numerous suppliers for retrofit system (Perpetuum, Railnova, televic-rail, wagon Tracker ADV, SKF…).
The Figure 1 and Figure 2 present the retained architectures in IMPACT2, RUN2RAIL and INNOWAG projects.
Some discussions with FR8RAIL leaders confirm that this approach is already validated and available using mostly MVB system to look at the global integrity of the locomotive (batteries level, location of the locomotive, engines, inverters…). The major contribution of LOCATE project is on the deployment of different methodologies defined into the different shift2rail projects focusing on the bogie. Indeed, LOCATE project scope of work is global: FMECA analysis, referenced based model approach evaluated into several shift2rail project, on-board measurement system and finally integration of the tool into maintenance protocol of the operator.
The main idea is therefore not to develop a new product but a methodology for the development of new plug-ins and demonstrate the value of using a digital twin to improve the maintenance of the locomotive.
It is important to note that most of the architecture are based on a on board unit that allow to reduce the data or/ and to define triggers to measure only a small dataset before any communication to a datacentre.
At this stage of the project, the methods and triggers are not known, the onboard unit system must be flexible, and it implies to separate raw data acquisition and time data reduction to be as flexible as possible.

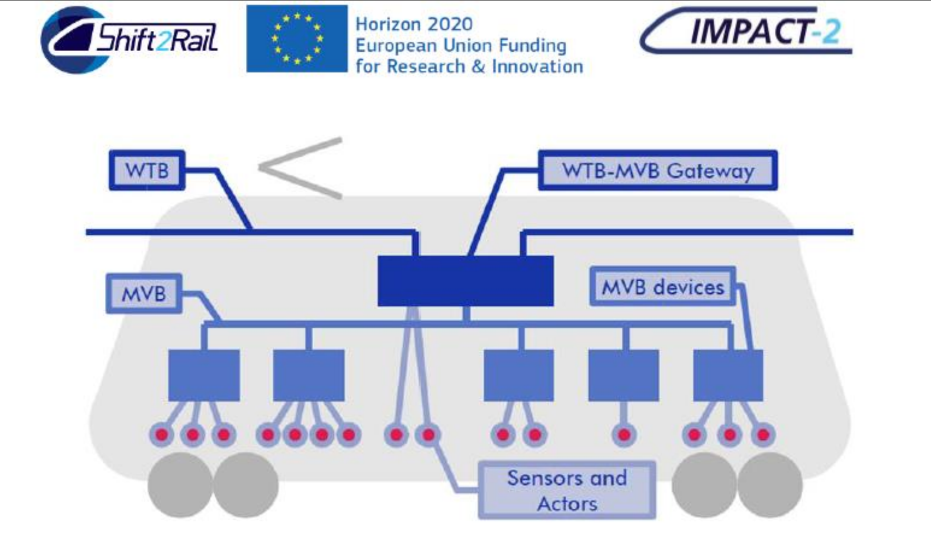


Figure 3 Overview data generating resources

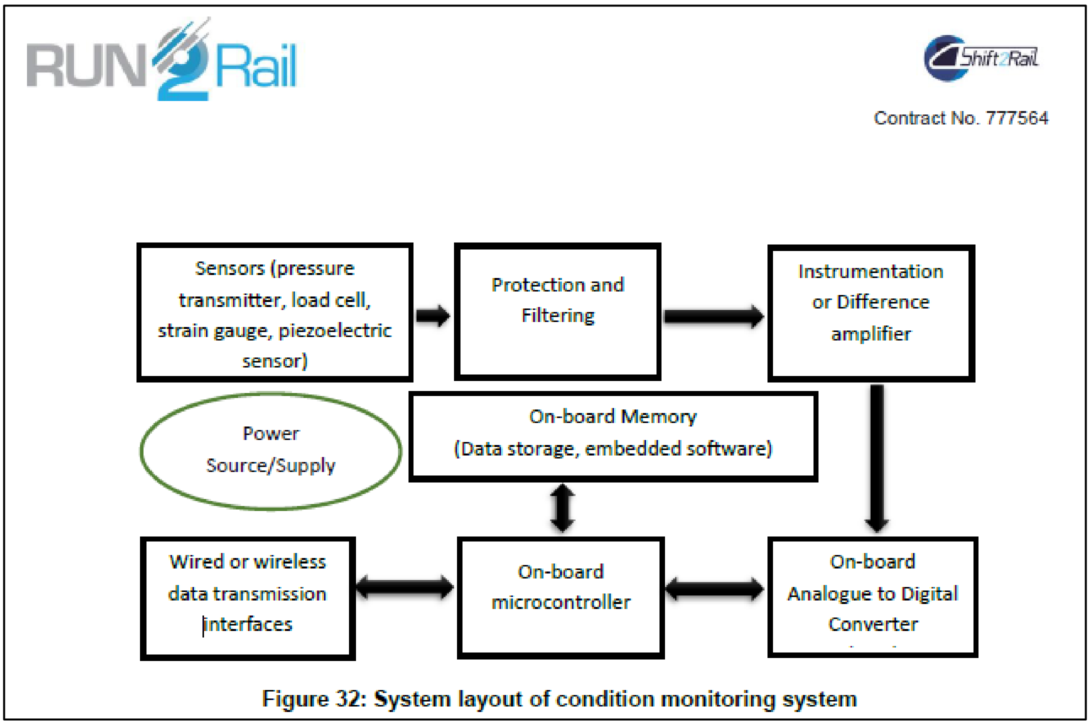


Figure 1 : Illustrations coming from shift2rail deliverables

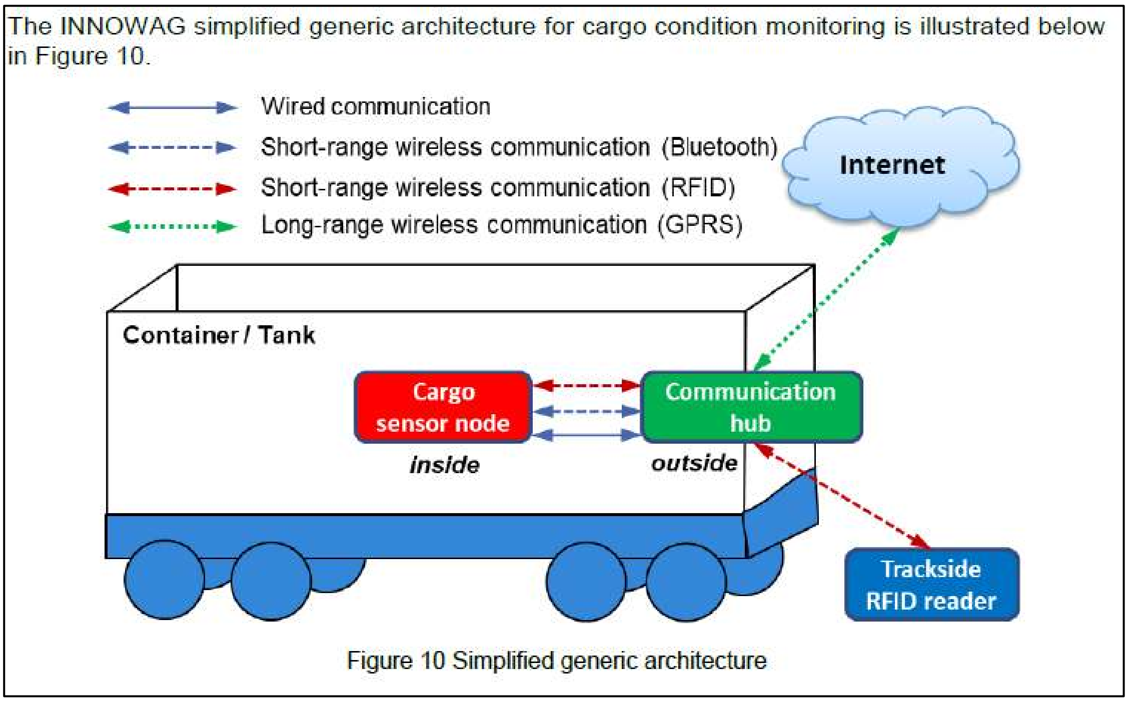


Figure 2 : global architecture coming from Innowag deliverables

RUN2RAIL is one of the shift2 rail project that goes deeply into sensor requirements and architecture on the following use cases (see ref. [7]):

- Condition monitoring of wheelsets,
- Condition monitoring of bearings and gearboxes,
- Condition monitoring of suspension components.

This deliverable gives requirements for the use cases that are closed to the ones of interest into LOCATE project. It misses only the bogie frame cracks detections. A first approach coming from D4.1 is to determine the periodic load applied to the bogie.

The Deliverable D1.1 of RUN2RAIL project is particularly interesting. It provides tables giving the relevant R&D references, the reported failure modes, and the sensor/physical quantity to measure.
An example of this table is given in Table 1. It presents the failure mode and physical quantity to measure to detect the failure.
Most of the proposed physical quantity are vibratory accelerations and strain.
Other physical quantity can give very relevant data on the health of the subsystems like temperature, viscosity of the oil, tension, current that are already present into the vehicle bus of the new generation of locomotive and are already subject to monitoring in FR8RAIL projects.

Failure mode addressed	Quantity to measure
Reduced efficiency of primary damper	Bounce, pitch and roll accelerations of the bogie
Failure of primary springs and dampers	Bogie frame acceleration above front and rear axle
Failure of primary springs and dampers and of secondary dampers	Vertical and lateral acceleration in the four corners of the car body, and bogies
Suspension component parameters; wheel-rail adhesion forces; wheel-rail profile estimation.	Lateral acceleration of bogie and carbody, yaw speed of bogie frame
Failure of actuators for an active wheelset	lateral and yaw accelerations of the wheelsets and bogie frame, yaw motion of each wheelset relative to the bogie (8 sensors)
Failure in yaw dampers, secondary vertical dampers, and secondary lateral dampers	Triaxial accelerometers (10 for each vehicle)
Suspension parameters (secondary lateral dampers and secondary lateral stiffness)	Carbody lateral acceleration over bogie frame, bogie lateral acceleration and yaw speed
Suspension parameters (secondary lateral dampers)	Carbody lateral acceleration over bogie frame, bogie lateral acceleration and yaw rate
Lateral damper degradation	Lateral acceleration and yaw velocity of the bogie, lateral acceleration of carbody
Vertical damper faults and vertical spring faults of both primary and secondary suspensions	Acceleration sensors in the four corners of the carbody and of the front and trail bogies
Secondary vertical damper fault, vertical spring fault and sensor failure.	Vertical acceleration and pitch acceleration of carbody and vertical acceleration of bogies
Secondary lateral and yaw dampers and equivalent conicity	Lateral accelerations of two wheelset, lateral acceleration and yaw velocity of the bogie, lateral acceleration of carbody
Secondary lateral and yaw dampers	Lateral accelerations of two wheelset, lateral acceleration and yaw rate of the bogie, lateral acceleration of carbody
Secondary vertical damper fault, vertical spring fault and sensor failure.	Vertical acceleration and pitch acceleration of carbody and vertical acceleration of bogies
Vertical primary springs and dampers	Four vertical accelerometers on axle box four vertical on bogie frame, one carbody
Yaw damper degradation, equivalent conicity	Bogie lateral accelerations

Table 1: Failure mode and corresponding physical quantity to measure. From Run2rail D1.1

The methods (model based or signal based methods) are based on the evaluation of the loads applied to the system of interest to determine if these loads are damaging the system or not (see ref. [9] to [13]). But the periodic loads applied to the system of interest are not easy to measure directly and the preferred way to determine the loads is to measure the dynamic response of the subsystem using accelerometers and/or strain gages.
These dynamic signals are also used to determine the natural frequencies of the system (modal response of the system) and failure detection is since the modal response of the system might not change.

5.2. On the sensor technologies / post processing needed signal

Regarding the retained use cases and the available model Assessment (report D4.1), most of the methodologies are based on the dynamic response of the system to monitor. The dynamic response of the system is the composition of the dynamic excitations and its natural dynamic behaviour (modal response).
The frequency band of interest are then highly dependent of the system and the damaging excitations. The Table 2 presents different frequency bands of interest in function of the system and the damaging excitations to monitor. This is also well described in [1].

System	Phenomenon	Frequency band (Hz)
Bogie	stability	0-50
Axle box	Bearing default	1000-20 000
Suspension	Cracks	1000- 20 000
Axle	Cracks propagation	500-2000
Wheel	Flat on the wheel	10-1000 Hz
Brake	Temperature monitoring	-

Table 2 : Frequency band of interest in function of system and phenomenon to detect

Work package 4 will focus on the assessment of available models based mostly on dynamic behaviour of the bogie to detect suspension defect or instability phenomenon due to modification of the rigid body modes of the locomotive.
Most of the known methods are based on dynamic acceleration sensors. Raw data are filtered or cross-correlated to evaluate instability problems. Such methods need high bandwidth, synchronicity in acquisitions and a good signal over noise ratio.
It will also need computational resources on the acquisition part to be able to reduce the data adequately (PSD, synchronous average, kurtogram, Kalmann filters….).
Ref. [11] gives a good overview of the different methods proposed in the literature and LOCATE will have to deal with.

At this stage of project, no methods are already clearly identified but most of them are based on the retained technologies:

- piezo electric sensors for high frequency acceleration (>1kHz): gearbox, bearings, cracks
- piezo resistive MEMs for low frequency acceleration (<100Hz): bogie stability, wheel flat, important cracks

Most of the indicators in the literature need a normalization of the dynamic response of the system in function of parameters as vehicle speed, curvature of the track, temperature, load of the locomotive. This normalization can be computed using a model-based approach ([13]) or adjusted using a statistical approach ([10]).
Additional sensor had to be installed on the locomotive to be able to do such normalization: GPS, current clamp to determine the requested torque, a tachometer to measure the instantaneous speed of the wheel, a gyro to determine the curvature.

6. Constraints

There are constraints located at different levels of the project: the locomotive age, the environment and retained approach into LOCATE project (preliminary campaign and long-term campaign).

The project itself:
Use cases and condition-based monitoring strategies will evolve during the project. Indeed, the model-based approach need some data that perhaps will not be available (track irregularities, physical properties of mechanical elements) and/or will give instrumentation specifications at the end of the project.
The option to do a preliminary measurement campaign to characterize the track and the rolling stock behaviour is also a constraint because it implies to have a flexible solution to re-use the system for long term measurement campaign.
Having a flexible data acquisition system is a key point to deal with the uncertainties in terms of sensor technologies and numbers of channels.
Then an existing monitoring system cannot be used because it will not be as flexible as requested by the LOCATE project.

The locomotive itself:
The locomotive was built in 1990, it is 30 years old. This generation of locomotive does not have any MVB. Most of the CBM platforms are based on the use of the information supplied by MVB.
Indeed, MVB brings a lot of information concerning the status of the locomotive: load, warnings, electrical consumption, vehicle speed, battery level…
The lack of MVB prerequisites to put additional sensor to have a view of the torque of the electrical engines, the wheel speed of the locomotive and temperature.
The cabin is small and there is no accessory board or onboard unit system location.
There is no cable duct between cabin and bogie already in place.

The environment:
The locomotives are used to transport potash which is a highly corrosive product. The locomotive operates between Suria and Barcelona in Catalogna, temperature is between 1°C and 34°C.
Due to sensor positioning, some ballast can impact the sensor.
The sensors and conditioning systems will be positioned outside the cabin and must fulfil the environmental conditions (IP67 rate and use protection covers).

Power supply:

The available power supply is a 72V DC supply on only one of the 2 cabins which is already equipped with a video recorder system.
There is a DC converter in this cabin. We should be able to use this power supply.

Size of the system:
The available spaces inside the cabin are presented in Figure 4. This area will be useful to put the acquisition system and OBU system.

The available position outside the cabin is situated along the long member of the cabin part (see Figure 3). This position can be used to put the conditioning system.

Figure 3 : Available position on outside part of the cabin to put the conditioning system

Figure 4 : Available spaces inside the cabin

7. Requirements

Below the LOCATE project main requirements are structured in a table with means of verification that the specific requirement was fulfilled and when associated, the respective Test.

Requirements			Testing	
Req. ID	**Requirements Description**	**Means of Verification**	**Test Description**	**Test Result**
REQ001	The installation should be done minimizing the number and severity actions on the locomotive and following the applicable normative and standards	Certification of the installer		
REQ002	All the devices, including sensors, wires and conditioner should be firmly fastened to the locomotive to resist physical efforts during operation	Preliminary test campaign	Test in operation	No degradation or damage in the equipment
REQ003	All the devices exposed to corrosion, including sensors, wires and conditioner should be resistant or covered.	Preliminary test campaign	Test in operation	No degradation or damage in the equipment
REQ004	All the devices exposed to weather conditions, including sensors, wires and conditioner should be resistant to the weather conditions or covered.	Preliminary test campaign	Test in operation	No degradation or damage in the equipment
REQ005	The system will guarantee its functionality at maximum train velocity (90 km/h) plus 5% overspeed	Preliminary test campaign	Test in operation	No degradation or damage in the equipment

REQ006	The onboard equipment must be protected against both radiated and conducted interferences and restrict the emission of those	Preliminary test campaign	Test in operation	Signals not affected
REQ007	The system must require low number of maintenance actions. Any action should have the lowest possible frequency, guaranteeing that this frequency is lower than the planned interventions frequency	RAM studies of components and combination of them	Suppliers data analysis	Foreseen time between failures lower than time between inspections
REQ008	The system should inform about the current health status of the monitored components, keep historical data and foreseen the future status, sending the corresponding alarms and recommendations to the maintainer	T6.4 System Validation and Results Evaluation	System evaluation	Positive evaluation
REQ009	The system should provide locational information from a GPS system or equivalent (e.g., latitude and longitude)	Preliminary test campaign	Test in operation	Correct Location Detected
REQ010	Vehicle speed should also be recorded (if available), possibly from the GPS system	Preliminary test campaign	Test in operation	Correct Speed Detected
REQ011	Specification of accelerometer sensors should consider. Axlebox acceleration of up +/- 200g at axlebox and axle. Sensors mounted on the bogie should be +/- 50g. Temperature range -50 to 120 Deg C.	List of Components	N/A	
REQ012	An appropriate sampling frequency for sensors should applied (e.g., axlebox accelerations at 4kHz and bogie accelerations at 2kHz to account for Nyquist)	Preliminary test campaign	N/A	
REQ013	Rugged design (e.g., EN 61373:2010 Railway applications — Rolling stock equipment — Shock and vibration tests), IP67, resistant to corrosion, low power consumption, ISO 9001	Specification of Components	N/A	
REQ014	The system architecture should consider including appropriate alarms to identify particular events. Severity levels from modelling and engineering know-how should be installed against each alarm.	T6.4 System Validation and Results Evaluation	N/A	
REQ015	Data storage of local events should be considered. Event recording should be done to conserve storage. In the development of the system architecture consideration of how much data is stored and what triggers the storage should be considered to minimise system component in-line with energy conservation of the system. E.g., axlebox accelerations at 4kHz would be very intensive data storage activity on long haul journeys. Consideration of what an event/alarm will record will help to define the system component architecture.	D3.5 Datasets Specification	Storage Capacity Evaluation	Storage Capacity increased several times, with same memory.
REQ016	Wireless communication of critical data and event should be considered. Appropriate comms for this should considered.	T6.3- Tests and Verification	Test Communications	Bandwidth and Latency within expected

REQ017	MIMOSA Standard may be useful in the development of the system.	T6.4 System Validation and Results Evaluation	N/A	
REQ018	The monitoring system should periodically transfer the minimal datasets to a central server	T3.4- Onboard data processing and communications	Communications Verifications	Delay between data exchange within parameters
REQ019	The system should periodically evaluate the need for interventions	T6.4 System Validation and Results Evaluation	Verify LOCATE Demo Outputs	Curve of Survival should regularly be updated.
REQ020	Data acquisition hardware: -40 to 85 Deg C, Shock resistant up to 30g.	List of Components and Datasheet	N/A	
REQ021	Security should be ensured within all communications.	T3.4- Onboard data processing and communications	Verify Security Implementations	Test OK
REQ022	Data accessibility should be considered in the system architecture. System architecture should consider the data management system and interoperability with other systems within the organisation and outside. MIMOSA ISO 13374 and RSSB T1010	List of Components	N/A	
REQ023	The Measurement System should be possible to implement using COTS components;	List of Components	N/A	
REQ024	The OBU should not interfere with the railway system onboard the locomotive	LOCATE System Architecture	Verify Behaviour with OBU ON/OFF	No difference in Behaviour
REQ025	The OBU should continuously communicate the minimal datasets and retrieve warnings by 4G or other type of connection.	T6.3- Tests and Verification	Verify Communications	Test OK
REQ026	The OBU should transfer logs and available raw data when within range of a trusted Wi-Fi network	T6.3- Tests and Verification	Verify Communications	Test OK
REQ027	The OBU should run LabVIEW and MATLAB programs to pre-process the measured data	T3.4- Onboard data processing and communications	N/A	
REQ028	The OBU should store at least the last 5 days of data on local memory	T3.4- Onboard data processing and communications	Verify Data History	Last Data >= than 5 days
REQ029	The OBU should have an interface to provide warnings to the driver.	T3.4- Onboard data processing and communications	Verify OBU GUI Output	GUI of OBU Functional
REQ030	The Data Acquisition System should allow mix and match of different sensor types.	List of Components and Datasheet	N/A	
REQ031	The Data Acquisition System should allow to change acquisition parameters, including number of samples, sample rate and others.	List of Components and Datasheet	N/A	

REQ032	The server should be able to exchange data with different systems, such as the OBU, Digital Twins Platform, and Maintenance Application	T4.2- Data Collection & Design of Computational Experiments	Verify Communications	Test OK
REQ033	The server should continuously evaluate the condition of a specific component in a Locomotive Bogie and report the 'component health' status	T4.5- Comparison of Reference and Measured Behaviour	Verify Results of Comparisons	Different results along time.
REQ034	The Maintenance Application should have the enough functions to demonstrate LOCATE Project Results	T5.7- SW Interface with Maintenance & Asset Mgmt.	N/A	
REQ035	The Maintenance Application should interact with existing Maintenance Software (ERP or others) or allow manual introduction of already planned activities	T5.7- SW Interface with Maintenance & Asset Mgmt.	Verify Introductions of events in calendar	Test OK
REQ036	The Server, with the Maintenance Application, should suggest unplanned maintenance scenarios and rescheduling of existing ones.	T5.7- SW Interface with Maintenance & Asset Mgmt.	Simulated Unplanned Event	Planned Events rescheduled
REQ037	In addition to the location (GPS) and vehicle speed information; the system should acquire the time/date of an event along with the direction of the locomotive (e.g., leading/trailing end)	T3.4- Onboard data processing and communications	Verify Time Stamp in Logs	Test OK

8. Instrumentation corresponding to use cases

Regarding all the developed methodologies concerning these three retained use cases and regarding the digital twin needs to enhance the approach. The instrumentation will mainly be based on the measurement of low frequency acceleration to monitor the dynamic motion of the locomotive and mid to high frequency acceleration to monitor the axle box and wheel set wear.

Due to the lack of MVB system in the locomotive additional measurement will have to be set to have a good idea of the load applied to the locomotive and the wheel speed.

Additionally, a GPS will be added to position the locomotive and have the skill to adapt the algorithm to the track condition.
An overview of the instrumentation is given in Figure 5. This set up is the one defined for the first measurement campaign and it will certainly be adjusted for the second part for CBM session regarding the other work packages conclusions.

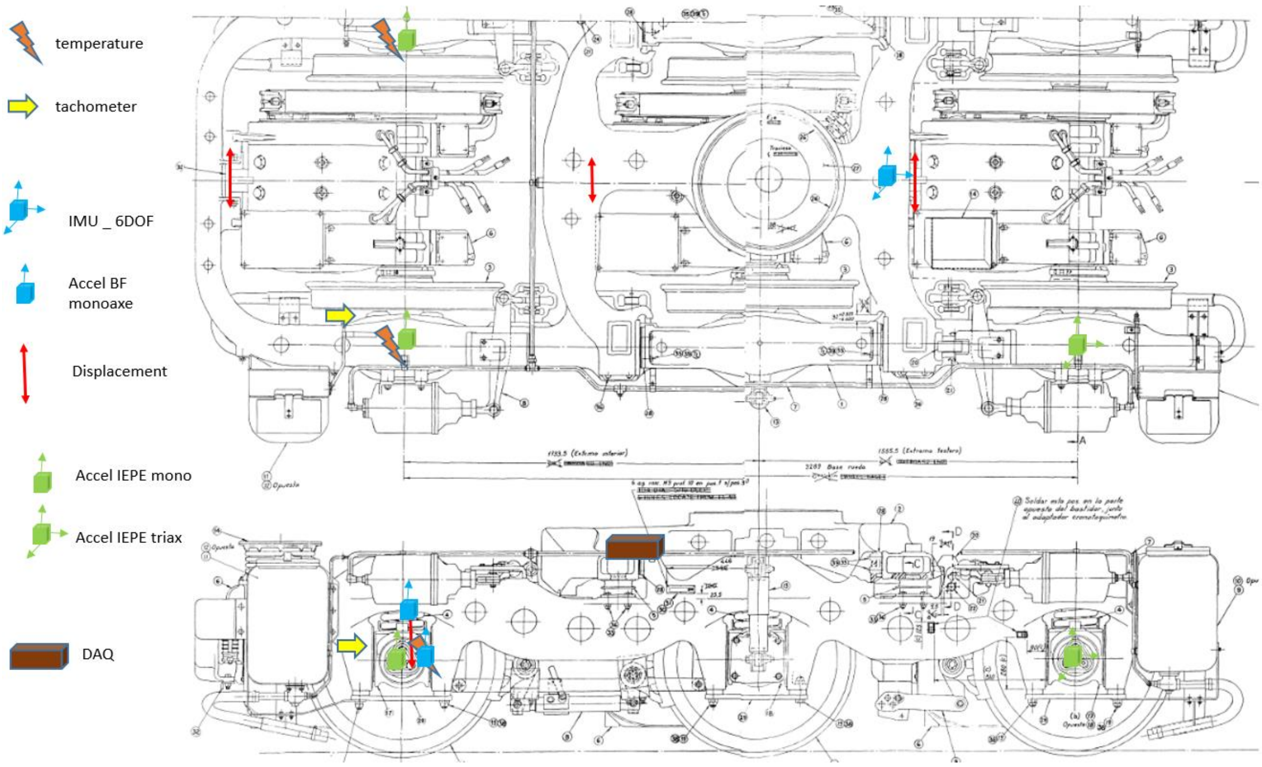


Figure 5 : Overview of the instrumentation for the two-measurement campaign.

A detailed review of the selected sensors is presented in deliverable D3.1 “assessment of available technologies”.

8.1. Sensor technologies

The sensors technologies will be:

1. High frequency accelerometers based on piezo-electric technology (10kHz)
2. Low frequency accelerometers based on Mems technologies (0-20Hz)
3. Displacement sensor
4. Inertial measurement Unit
5. Temperature probes
6. GPS
7. Tachometers
8. DC current clamps

A presentation of the most critical sensors technologies will be done in next chapters. It concerns low frequency accelerometers and displacement sensors.

8.2. Sampling frequencies

For dynamic motion measurement the frequency band of interest is [0-20 Hz] to detect rigid body modes of the bogie. These rigid body modes will normally be modified if the primary suspensions

are evolving (decrease of damping, breakage of a spring).
For wheel set wears the frequency band of interest is [500-2500Hz] depending on locomotive speed and mechanical architecture of the sub-system.
For bearing defects, the frequency band of interest is [1 - 20 kHz] to detect most of the bearing defaults (outer ring, inner ring, rolling element).

8.3. Bogie stability

3 sensors will be installed: Inertial Measurement Unit (IMU) on central beam of bogie, 2 low frequency accelerometers.

The sensors dimensions are approximately 20x20x20 mm weighting less than 100 grams.

Figure 6 : IMU suggested location: flat, easy access, centre of bogie, protected…

Figure 7 : Close-up view of the location.

Figure 8 : Transversal accelerometers positions.

Figure 9 : Close-up view of accelerometer position (behind the hydraulic system of the brake = protected area)

8.4. Axle box measurement

The same type of sensors as for the bogie will equipped the axle box.
1 or 2 tachometers will be added to measure the wheel speed of the train using a magnet glued on the wheel and magnetic probes.

Accelerometers will be positioned on 3 axle boxes as illustrated on the following figures.

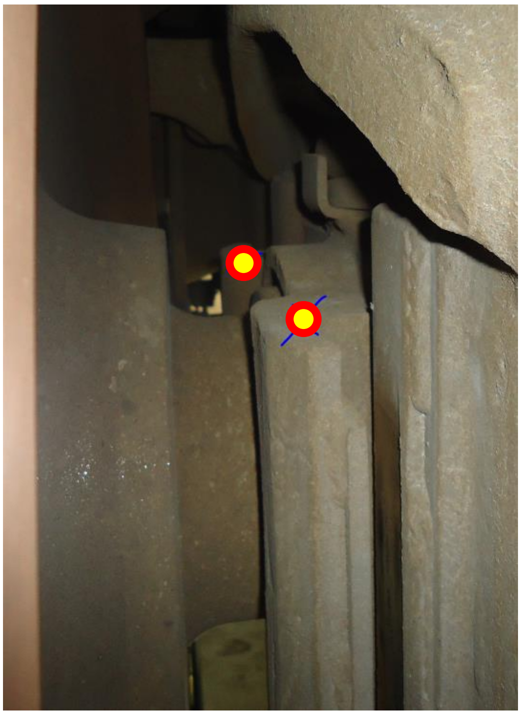


Figure 10 : On wheel side: preferred (protected and in the wagon gauge)

Figure 11 : Outside view: green: temperature measurement (use bolt to fix the system or use thermocouple gauge directly glued on the surface…)

8.5. Electric engine

Torque will be measured using indirect strategy if intensity probes cannot be implemented. A displacement sensor on the rear rubber mounts of each electric engines will set. It will give an indirect measurement of the torque of the electrical engine. This instrumentation is the best option to have an information relative to the load of the locomotive due to the lack of MVB system in the locomotive.
Indeed, the applied torque of the engine to the wheel will create a reaction force at rear suspensions. The suspension will crush in function of the applied torque.

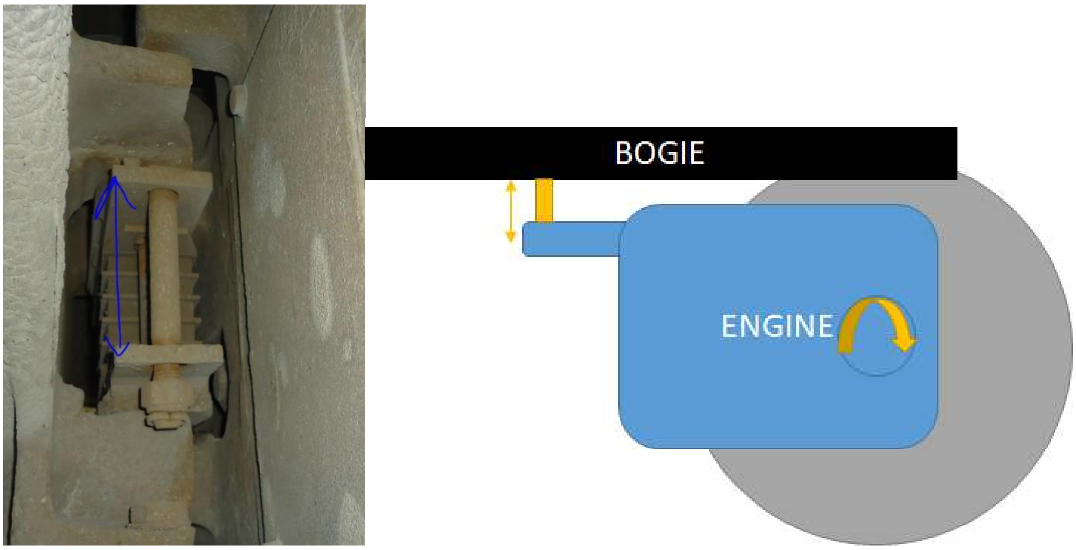


Figure 12- Displacement sensor position and schematic view of measurement principle

Temperature measurement is not requested.

8.6. Tachometer

Due to environmental condition, tachometer must be based on magnetic technology (Hall Effect, inductive, reluctance).

The tachometer can be set at different position (depending on the authorization given by FGC):
- On the axle box with a magnetic target added on the wheel
- In the gearbox with a gear as a target

8.7. Brakes

Temperature sensors are to be installed on the braking system to monitor this parameter while driving.

Other monitoring possibilities are not considered on this project because it would not be economically feasible compared to traditional human monitoring techniques, since brake shoes are visible for example (inspections of the components).

9. Specifications / architecture

9.1. Overall System

Figure 13 shows the overall system architecture and data flow between its components.

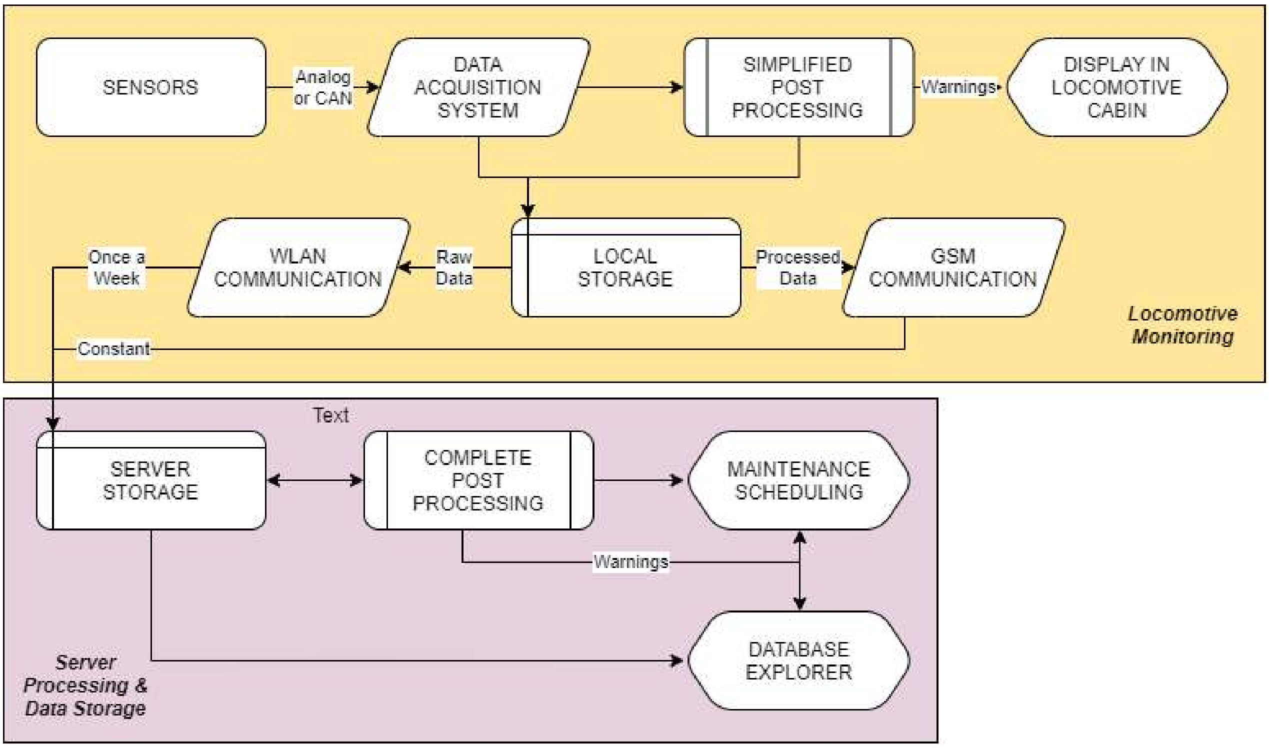


Figure 13 : Overall system architecture. Protocols are examples of what can be used, with equivalent technologies as possible replacements.

Acquired data from sensors is acquired either directly or after some conditioning (e.g., noise filters, analog to digital conversion closer to sensor). Raw data can be fully stored locally, at least during development. This is intended to gather enough data to enable the correct identification of important deviations. Once this is achieved the amount of raw data saved can be reduced by flagging interesting portions through the simplified post processing.

This simplified processing should also be able to identify relevant warnings that necessitate immediate action to be displayed inside the locomotive's cabin. The system overall status could also be visible through this system.

From local storage relevant data identified by the simplified processing can be immediately transferred to a central server for logging through a GSM connection. Once a week, or another agreed upon period, locally stored data should be transferred to the central server, releasing the storage for the next acquisition period. This transfer should be done over a faster and cheaper communication method, such as wireless local area network (WLAN).

This complete data can then be fully processed, including comparison with the digital twin running as part of this post processing system. The results of this processing will affect the maintenance schedule, either directly or through suggestions for manual time allocation.

Important warnings should be given a more active means of communication, such as notifications or emails to the relevant people. These notifications could be displayed in the database explorer, which should also allow the user to browse both the full raw data and processed results.

9.2. Locomotive Monitoring

Figure 14 presents an example of the architecture for the sensor's installation on a locomotive. It is composed of:

- OBU inside the cabin
- Conditioning system outside the cabin
- Analog sensors on the sub systems

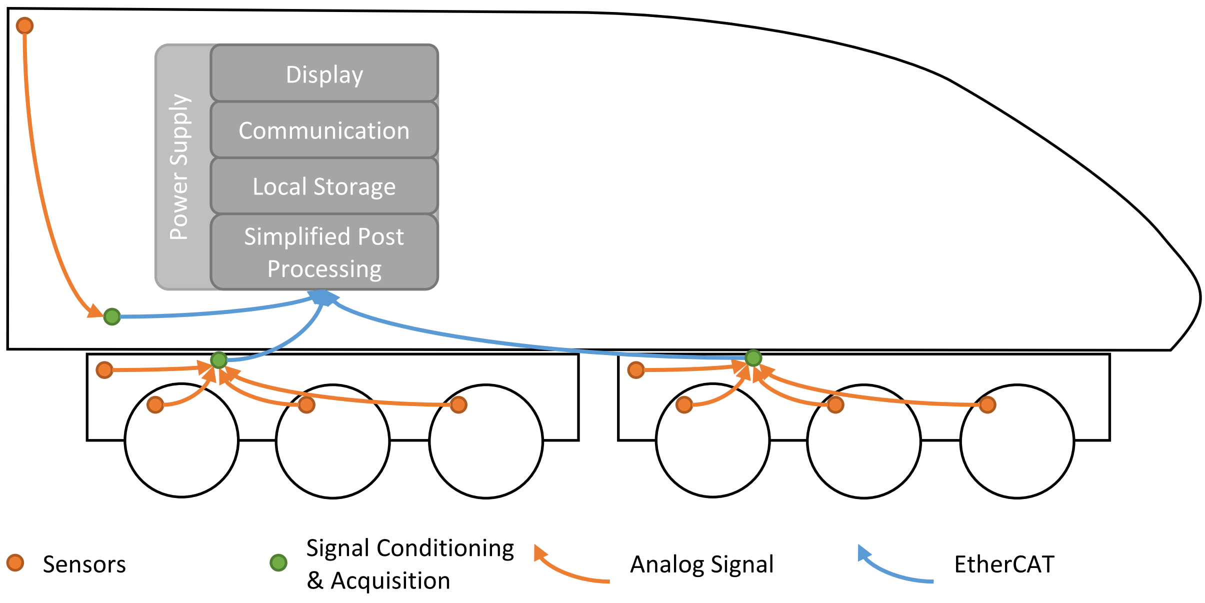


Figure 14 : Overview of an example architecture.

The power supply draws power from available power lines in the locomotive (72 V DC) and feeds the entire system. This could be composed of several modules for different voltages for different sub-systems.

Sensors should be connected to conditioning units on an at least per module level, reducing the number of connections to the central data gathering unit. More can be used according to local conditions. Any power to sensors should come from these conditioning units, if possible.

Communication between the conditioning units and the central unit should use a digital protocol, preferably with real-time capabilities to enable signal correlation. Technologies such as EtherCAT can be used for this purpose, with the server/controller running either on the computer responsible for storage and processing itself (which could be enough for development) or in a dedicated module with asynchronous communication with the computer. The technology should enable daisy chain connection between the different modules, reducing the number of wires going into the central unit. If individual module reliability is preferred a star connection can be used, with each module having its own connection to the central unit.

All the components should respect railway standards and volume restrictions.

9.3. OBU [OnBoard Unit]

The OBU is responsible for:

- Raw data aggregation.
- Simplified analysis.
- Raw data and analysis results storage.
- Communication with server.
- Display of status / warnings.

These functions can be achieved with a single computer or a distributed system. For example, data aggregation can use the computer as an EtherCAT server or use a dedicated module with asynchronous communication with the computer.

Local storage should be both fast enough for the large amount of data being acquired and large enough for the considered period between downloads to the central server. This means technologies such as RAID stacks and even SSD drives should be considered. For development full raw data can be stored, but this can be reduced by identifying relevant portions of the signal for further processing at a later analysis.

By processing data in a simplified manner relevant warning should be identified and shown on the cabin display. This display can be a dedicated screen but could be integrated with the locomotive's own status display in a fully integrated system.

System requirements for the simplified processing must be determined during product development. However, the system must run a Windows OS, capable of running LabVIEW Runtime, MATLAB MCR and or Python code or other executable code.

The communications include two parallel systems: a GSM connection for continuous connection with the central server, sharing relevant warnings in real time and a local connection (e.g., WLAN) to back up all the acquired data at established periods.

9.4. Sensor and conditioning system

The conditioning system must be flexible to accommodate different types of sensors (MEMs, potentiometer, tachometer, thermocouples, GPS) and with different bandwidths while limiting the time of setting and encoding. This system must offer enough flexibility to be able to modify the types of conditioning to be usable on both the characterization campaign and the monitoring campaign.

Table 3 presents a synthesis of the specifications.

OBU	
SP-1	power supply 72V DC
SP-2	windows 7 minimum
SP-3	8Gb Ram
SP-4	256Gb
SP-5	WAN and 4G router
conditioning system	
SP-6	outdoor
SP-7	corrosive
SP-8	impact from ballast
SP-9	empowered by OBU
SP-10	multi sampling rates (1, 20Hz, 5kHz)
SP-11	multi sensor conditioning (Mems, IEPE, potentiometric, tachometer)
sensors	
SP-12	IP67
SP-13	corrosive environment
SP-14	waterproof connectors
SP-15	impact from ballast
SP-16	CEM protected (shielded cable)
SP-17	shock resistant

Table 3 : Specification synthesis

Table 4 is edited to give an overview of the sensors position and associated system to monitor

Sensors	target	frequency
Vertical acceleration on 2 axle boxes	Bearing of axle box, wheel flat, wheel roundness, dynamic loads due to track defaults	0-20 kHz
Longitudinal acceleration on axle box	Axle cracks	0-10 kHz
Low frequency accelerometers on the bogie	Rigid body modes of the bogie to detect instability and evaluate degradation of suspension components and important damage of bogie frame	0-50 Hz

Inertial Measurement Unit close to the centre of gravity of the bogie	Dynamic motion of the bogie, main target is to determine curvatures, inclination and try to identify modal response of the bogie frame	0-50 Hz
Tachometer	Wheel speed for post processing measurement signal, definition of threshold	-
GPS	Possibility to focus on some representative track sections	10 Hz
Current clamp on electrical engines	Be able to determine the requested torque to determine triggers or conditions of analysis	100 Hz
Temperature Probe – brake system	Exceeding a threshold temperature. Association of the temperature with certain events	-

Table 4 : Sensor list and targeted monitoring reasons

Evaluations of suppliers

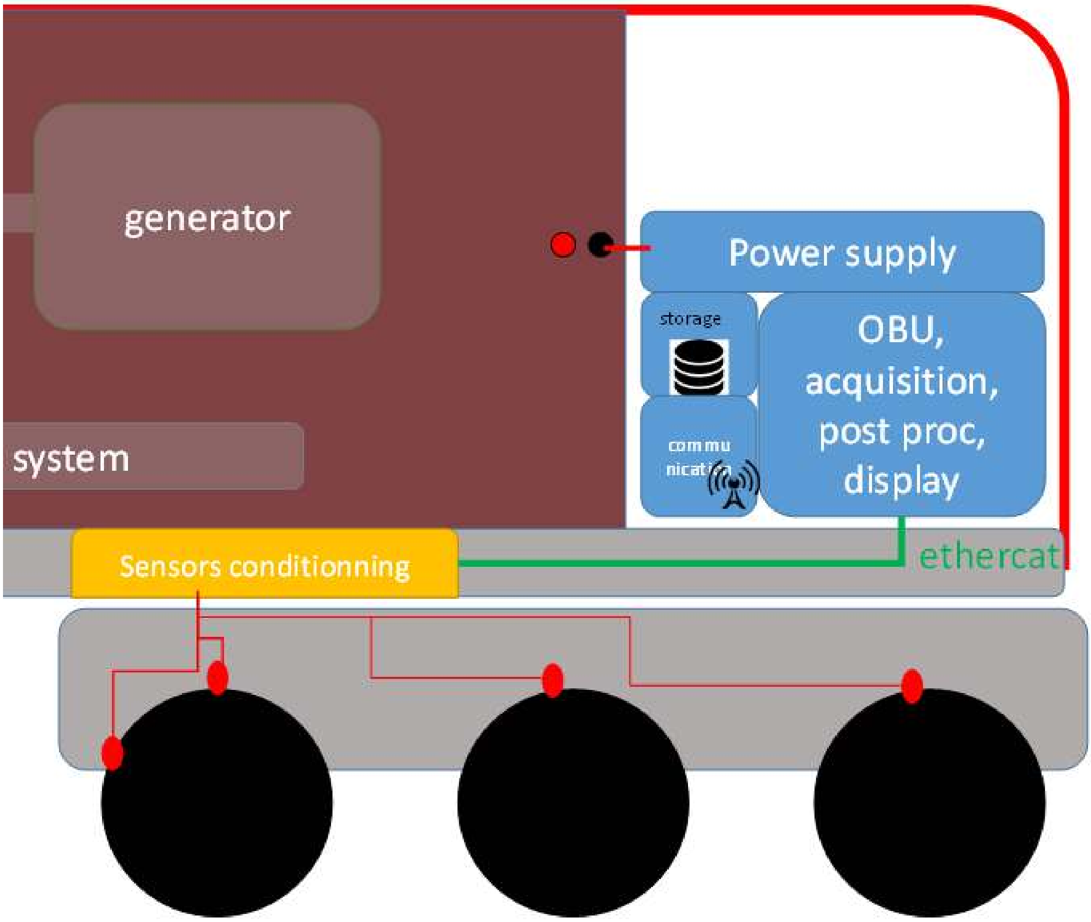
DAQ (data acquisition) system dedicated to measurement is best positioned and sufficiently open and not more expensive than a dedicated system.

The following suppliers were evaluated IMC, DEWESOFT, HBM, GANTNER.

Dewesoft was retained due to cost, robustness, ease of use and possibility to develop easily post processing tools with supplied libraries.

Cost overview

Sub-system	Price (€)
Power Supply	400 – 500
Central Unit	2500 – 3000
Communication	~1000
Conditioning	~16000
Sensors	8000 – 10000


generator
system
Power supply
storage
commu
nicati
OBU,
acquisition,
post proc,
display
Sensors conditionning
ethercat

10. Conclusions

This document presented the overall and detailed System Architecture capable of implementing the use case specified, addressing the associated requirements.

At this stage of the project, it is agreed that the monitoring system would be composed of:

- OBU inside the cabin
- Conditioning system outside the cabin
- Analog sensors on the sub systems

The following suppliers were evaluated IMC, DEWESOFT, HBM, and GANTNER.
DEWESOFT was retained due to cost, robustness, ease of use and possibility to develop easily post processing tools with supplied libraries

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