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# Deliverable D 6.2

# Predictive Maintenance Framework

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# 1. Executive Summary

Railway undertakings have made large investments in order to run the rail services economically and safely.
It has been proved that the Reliability, Availability, Maintainability and Safety (RAMS) are pre-requirements for a reliable and attractive rail service. Furthermore, the European directive EU 2016/798 requires that every vehicle on a railway must be operated safely. In practice, there is a balance between costs and:

- Reliability: The probability that an item can perform a required function under given conditions for a given time interval of time.
- Availability: The ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.
- Maintainability: The probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.
- Safety: Freedom from unacceptable risk of harm.

The aim of this 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.

The overall concept of LOCATE is to set-up a complete procedure from the observed performance of the bogie and associated sub-systems to the railway operator in order to provide them with reliable information about its condition and allowing decision-making in relation to proven maintenance plans and the component ageing and failure behaviour.

The implementation and evaluation of a full-scale demonstrator up to TRL 6 require achieving three separate objectives:

1. Measured behaviour: setting-up a complete measurement chain with high integrity from bogie sub-system to operator.
2. Reference behaviour: defining threshold values and reference condition criteria from existing maintenance plans, component functional and safety requirements, and sensor capability.
3. Operational behaviour: setting-up a new framework of a predictive maintenance program based on the capability of the installed monitoring system, the optimized maintenance schedule, and operational constraints.

The purpose of this document is to give the conclusions of LOCATE on the 3rd objective “framework of a predictive program” to be applied on the bogie of the FGC freight locomotives.

# 2. Abbreviations and acronyms

| Abbreviation / Acronyms | Description |
|---|---|
| PdM | Predictive maintenance |
| CBM | Condition based maintenance |
| TRL | Technology Readiness Level for LOCATE level 6 demonstration of the technology in real environment |
| ECM | Entity in charge of the maintenance as defined in European regulations |
| RUL | Remaining useful life. Time during which the asset can be operated with an acceptable risk of having inacceptable defects |
| RU | Railway undertaker |
| CM | Condition Monitoring |
| RUL | Remaining Useful Life (time after which the risk of defect becomes intolerable) |
| MTTF | Mean Time To Failure |
| RBD | Reliability Block Diagram |
| PDF | Probability Density Function |
| CDF | Cumulative Distribution Function |
| MILP | Mixed-Integer Linear Programming |
| FMECA | Failure Modes, Effects and Criticality Analysis |
| WP | Work Package (LOCATE) |

# 3. Background

FGC has been operating the three diesel locomotives of type 254 since the early 1990s. A large amount of experience has been gathered in operation by the FGC teams (technical and fleet managing) since then.

FGC applies a scheme of maintenance of 4 levels, described in D2.1, based on

- Scheduled maintenance inspections
- Conditional maintenance triggered by previous actions
- Systematic maintenance operations carried out on a step according to the distance covered or the time spent
- Corrective maintenance, operations carried out after a non-foreseen defect in operation

In LOCATE, analyses of the defect modes and their consequences on the railway system (FMECA) have conducted and explained in D2.3. The following list is organised in descending order of risk level:

1) Braking system
2) Wheelset
3) Electric traction module
4) Axle box
5) Suspension elements
6) Bogie frame

The defect modes that can be addressed by the LOCATE methodology (comparison between digital twin and and data gathered by the sensor system on the locomotive) have been clearly identified.

Considering the interface between wheels and track and its impact on the vibrations of the bogie, it is important to notice that FGC is also in charge of the maintenance of the track.

LOCATE being focused on the maintenance of the bogie, we decided to limit the measurements used by LOCATE to specific parts of the lines on which the 254 locomotives are operated.

# 4. Objective/Aim

This deliverables aims to capture the End-to-End LOCATE Predictive Maintenance Framework and describing the system specification in terms of monitoring system and operational context. The system behaviour is also explained in their three axis: Reference, Measured and Operational Behaviours.

Then the system integration and validation results are presented and highlighted. The data collection process and analysis are presented as the reference model validation and key results. The LOCATE software front end is also presented with the most important features and the way the information is presented.

# 5. System Definition

The LOCATE system definition followed an approach based on three main axis:

- Reference behaviour with the aim to model and create a digital twin
- Operational behaviour with the goal to capture the operational aspects of the maintenance program
- Measured behaviour focused on the monitoring system that could provide the data to be processed and compared with the digital twin.

The LOCATE system integrates these three axis into a framework.

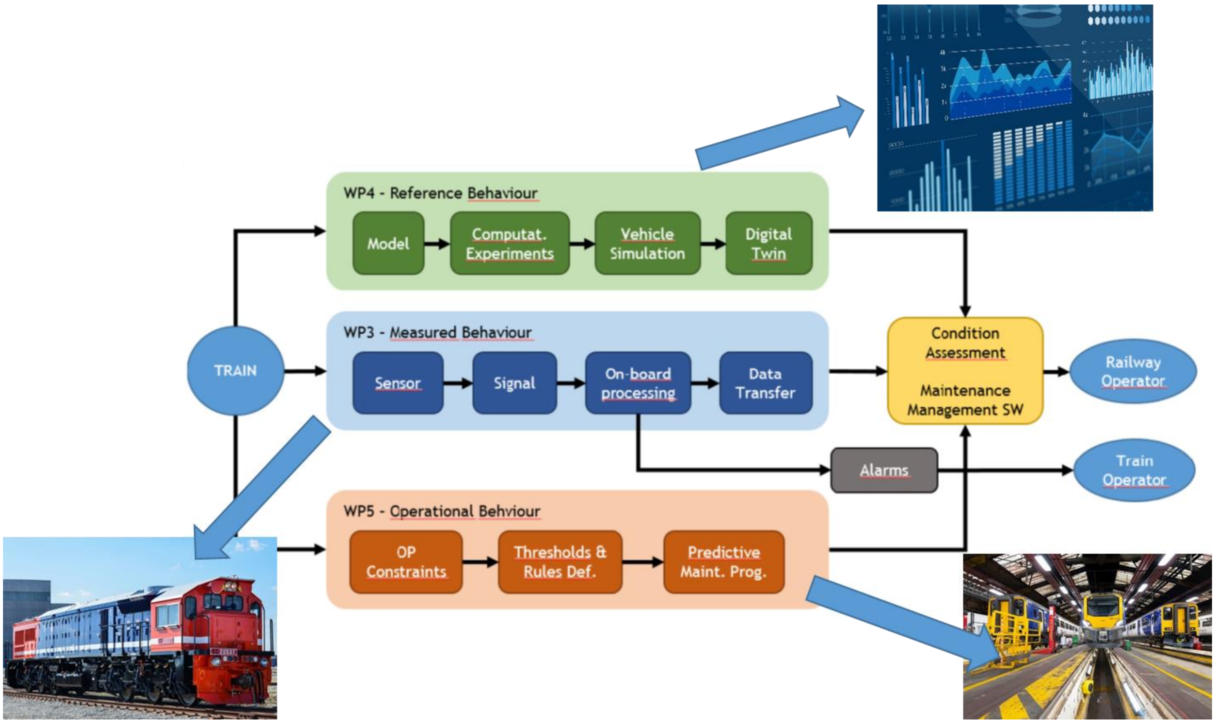



Figure 5-1: LOCATE Project organization

The following diagram depicts the different technology bricks and interactions.

The LOCATE architecture can be mainly divided into four main areas:

- Locomotive, which is composed by:
    - Sensors
    - Acquisition System
    - Edge Computer
    - Communications (Satellite Positioning and 4G/ 5G)
- Cloud, running a set of Web services:
    - Communications aggregation
    - Notifications service
    - Database
    - Processing service
    - Generation Report

  - Digital Twin and Reference Library
- Users Application Software, providing information for different user needs:
  - Near Real Time Notifications Dashboard
  - Maintenance Support Dashboard
- 3rd Party Maintenance Operations Tool Interface for:
  - Maintenance Operations Logic
  - Maintenance Operations Planning

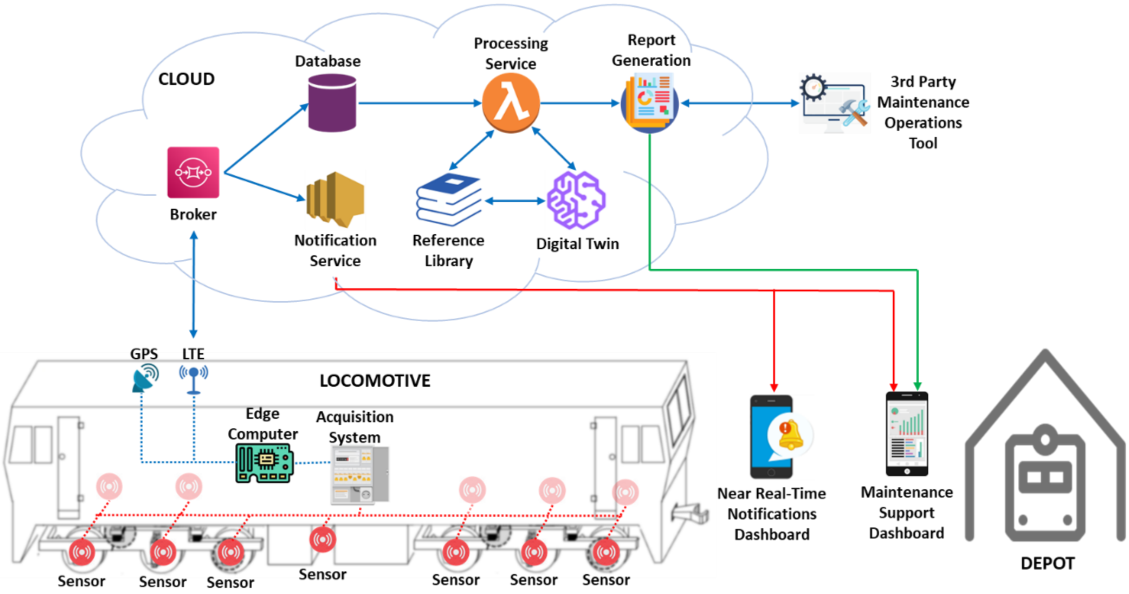



Figure 5-2: LOCATE Monitoring System Architecture Overview

# 6. Technical Specification

This chapter establishes the technical specification from the different areas of the LOCATE project, from the monitoring system to the operational aspects to be considered.

The use cases and subsystems to be monitored were identified and the Locomotives selected by FGC were the 254 series.

Based on the sub-systems candidates, the FMEA methodology was performed in order to identify and prioritize the most relevant systems, subsystems and components of the bogie and the Risk Priority Number (RPN) was used to rank the criticality of the failure modes identified. From the FMEA analysis results, the critical components of three main subsystems of the bogie were identified, namely:

- Wheelset
- Braking System
- Suspension System

Considering that FGC has also major problems regarding maintenance, number of failures or warnings and time to repair, with other types of subsystems, such as the bogie frame and the electric traction engine, a proposal was created that is aligned with the interests and research opportunities of the present project.

In this proposal, the most critical subsystems defined are the following:

1) Wheelset subsystems
2) Axlebox
3) Bogie Frame
4) Brake System
5) Suspension system / elements
6) Electric Traction Motor

## 6.1. Locomotive and Monitoring system

In this section the specification of the sensors for the LOCATE Monitoring System are defined. The chapter is divided into specification from a reference Model based on the digital twin modelling and the LOCATE demonstrator use case which includes the necessary adaptations in terms of specific installation that is usual on a retrofitting scenario.

### 6.1.1. Reference Model Sensors

The Reference Model here presented is the outcome of the WP4 – Reference Behaviour, more specifically the deliverable D4.3 Behaviour Prediction, Simulation and Post Processing Results Report which established the set of sensors to be used in the monitoring system.

The sensor system depicted in the following diagram is to detect damage in the bogie frame and primary suspension.

The system consists of six biaxial accelerometers (lateral and vertical directions), one on each axle box, four uniaxial accelerometers (lateral direction) on the bogie frame, and one IMU at the centre of the bogie frame that records longitudinal, lateral, and vertical accelerations and roll, pitch, and yaw speeds.

The IMU can be used to calculate the rigid body accelerations at other points in the bogie by differentiating angular velocities. Additionally, the yaw velocity measured by the IMU allows distinguishing straight and curved sections.

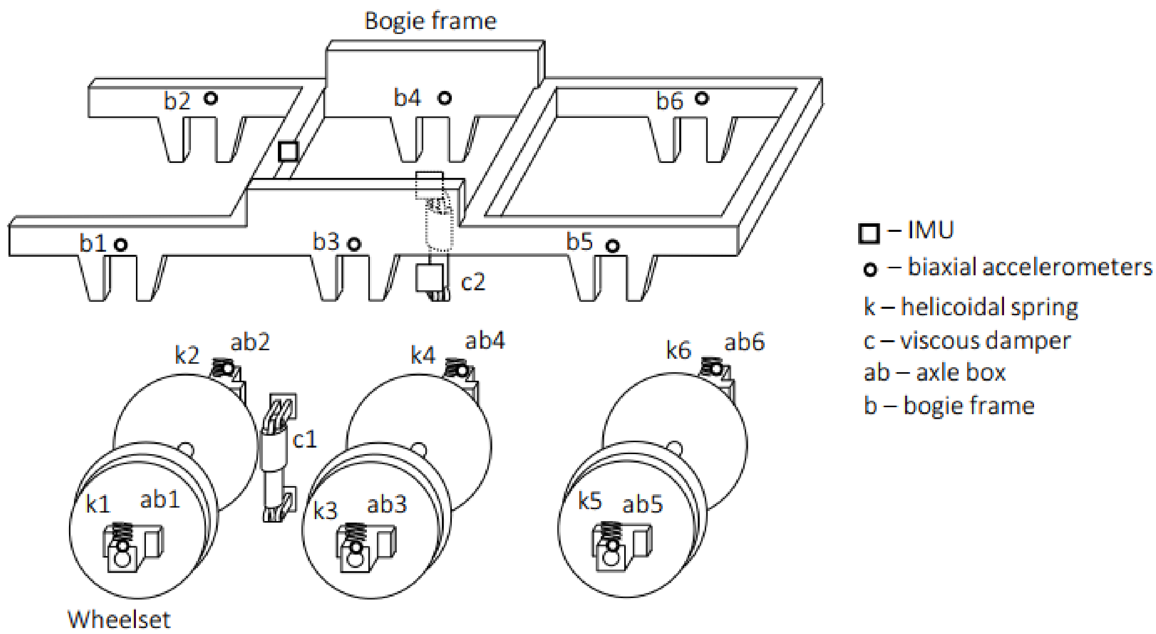



Figure 6-1: LOCATE Reference Model Sensor System

The goals and frequency domains required for each sensor are described in the following table.

| Type | Sensor | Direction | Frequency domain [Hz] | Monitored System |
|---|---|---|---|---|
| Uniaxial accelerometer | b1/b2/b5/b6 | Lateral (*y*) | 1-20 | Primary suspension |
| | | | 10-150 | Bogie frame |
| IMU | b10 | Lateral (*y*) | 1-150 | Bogie frame |
| | | Roll/Pitch/Yaw | 1-20 | Primary Suspension |
| Biaxial accelerometer | ab1/ab2/ab3/ ab4/ab5/ab6 | Lateral (*y*) | 1-20 | Primary suspension |
| | | Vertical (*z*) | 1-20 | Primary suspension |

Table 6-1: LOCATE Reference Model Sensors for damage detection in bogie frame and primary suspension

### 6.1.2. Demonstrator Sensors Setup

The LOCATE demonstrator setup took the advantage of a preliminary measurement campaign prior to the demonstrator, to learn the necessary adaptations to the specific retrofitting and operational constraints.

To address the use cases: axle box, electrical engines, bogie frame wear and springs the instrumentation should be able to:

- Detect rigid body modes and 10 first bending modes of the bogie
- Deflection of springs under static loads.
- Vibration level on axle
- Current consumption on the 3 electrical engines.
- Make the analysis on a predefined section of track using the GPS.
- Measure precisely the odometer using the installed digital encoder.

A schematic view of the instrumentation is given in following figures.

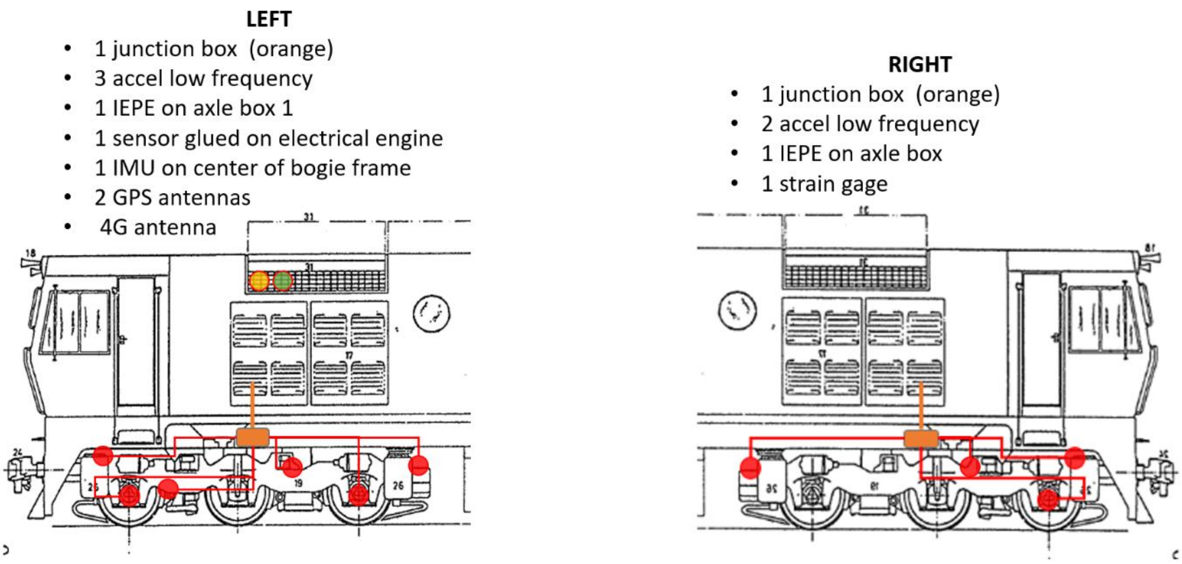



Figure 6-2: schematic view of instrumentation on bogie area

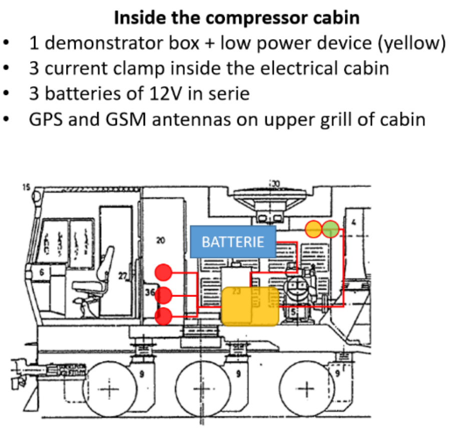



Figure 6-3: Schematic view of instrumentation inside the compressor cabin

The proposed instrumentation is presented in following table.

| Sensor | Fixation | Sub system | Comment |
|---|---|---|---|
| 4 Accelerometers | bi component epoxy glue | bogie Frame (corners) | |
| 3 accelerometers | bi component epoxy glue | 3 Axle box | Temperature included inside the sensor |
| 1 strain gages | Cyanolite glue | Bogie frame | Optional |
| IMU | bi component epoxy glue | Bogie frame (center) | |
| 1 sensor | glued (epoxy) | Carter of electrical engine | |
| 3 temperatures | bi component epoxy glue | demonstrator box and air compressor cabin | Optional |
| 3 current clamps | Not fixed (adhesive tape) | Electrical cabin | |
| 3 antennas (4G, 2 GPS) | Screwed | Upper grill of compressor cabin | |

Table 6-2: Proposed instrumentation and corresponding sub-system

As a list:

- 3 current clamps: one per electrical engine (0-50Hz)
- 2 temperature probes on: on 2 front axle boxes (included inside accelerometer)
  * An additional temperature sensor will be inside the demonstrator box to control maximum temperature of the acquisition system.
- 1 IMU (Inertial Measurement Unit) to compare the global dynamic motion of the bogie of the locomotive
- 1 dynamic strain gage on the bogie frame (x1) (0-200Hz): it allows to have a view of the bending modes of the bogie and the excitation frequencies (suspension of the wheels).
- 1 sensor on electrical engine to detect magnetic field to try having wheel speed (non-intrusive sensor).
- 4 accelerometers on the bogie to detect abnormal motion on first bending modes and rigid body modes of the locomotive. (0-200Hz)
- 3 accelerometers on the axle box to detect abnormal vibration on axle box: 0 -10kHz
- GPS to detect the track section and measure vibration on 2 sections of track.
- 4G antenna to communicate data to data centre.

The following figure illustrates the distribution of the instrumentation in the bogie.

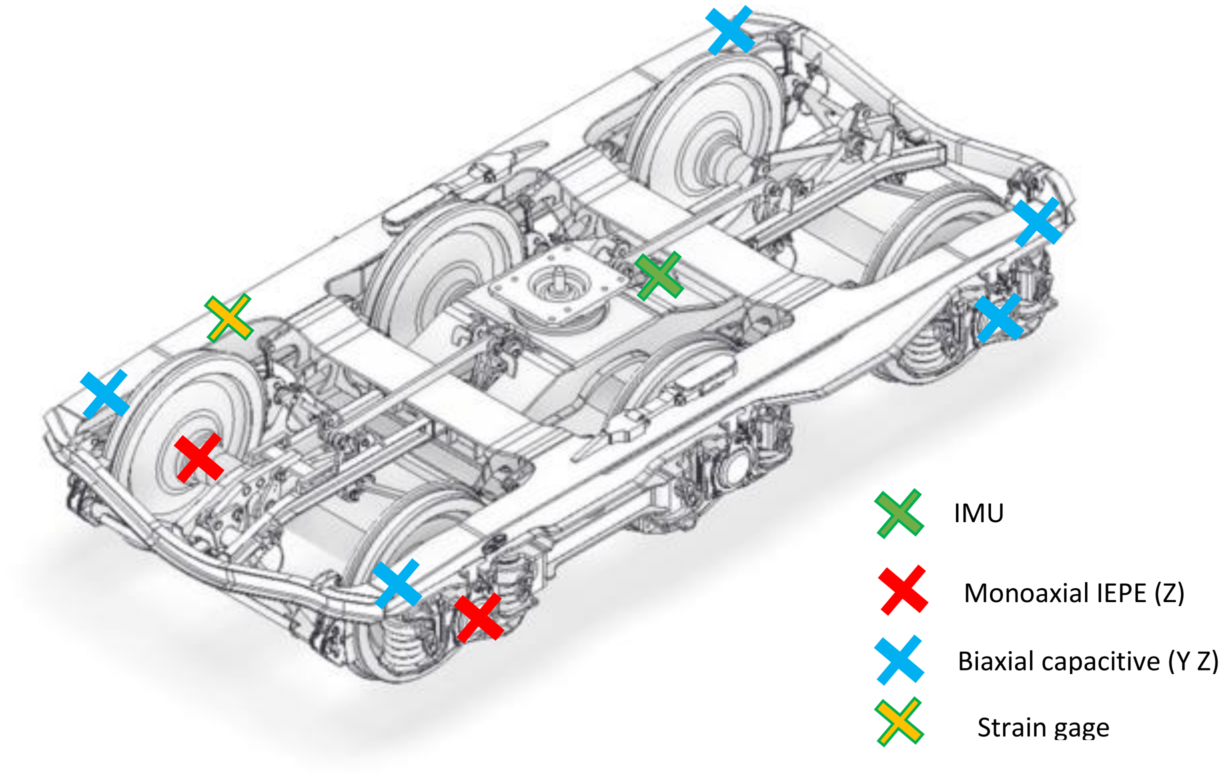



Figure 6-4: Location of Sensors on Bogie

There are also instruments inside the cabin:

- 3 current clamps (1 per engine) inside the electrical cabin,
- 2 GPS antenna + 1 GSM antenna

### 6.1.3. LOCATE Monitoring System Architecture Overview

This chapter presents the LOCATE Monitoring System overview in terms of overall architecture, data pipeline workflow and the different information exchange and interaction between the several technology bricks.

The data pipeline workflow is depicted in the following diagram.

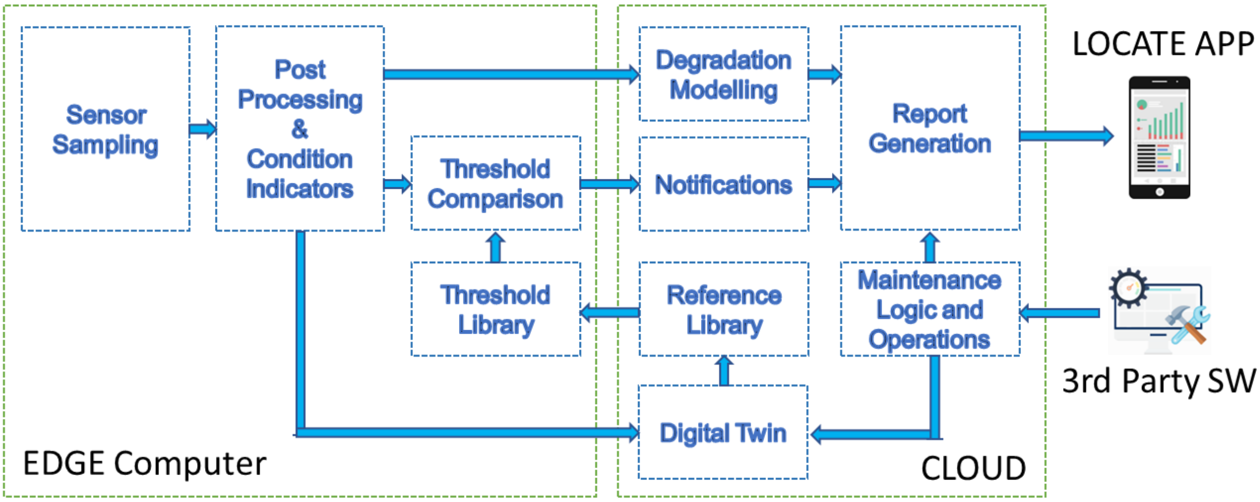



Figure 6-5: LOCATE Monitoring System Data Pipeline Workflow

The data from the sensors are acquired by the Edge Computer through the acquisition system. The sensor data is then processed and condition indicators are computed by comparing with the reference thresholds.

The processed data and condition indicators comparison is than pushed to the webservices running in the cloud.

The web services include:

- Degradation Modelling based on historical records is computed and inferred the Remaining Useful Life and life curve prediction of the components
- Notifications service for near real time notifications
- Maintenance Logic and Operations Planning interface to 3rd Party Software
- Report Generation
- Digital Twin based on simulations and labelled measurements that can be added to the Reference Library
- Reference Library containing simulated and measured labelled condition-based behaviours. The Reference Library thresholds are than downloaded to the Edge Computer for the Conditions Indicators threshold comparison.

The LOCATE App is based mainly in two dashboards, the first for end-users interested in near real-time notifications for decision support in a short-time frame (e.g. train driver or high priority maintenance intervention reaction needed). The second dashboard is for maintenance decision support.

The interface to the 3rd Party Software is to enable the integration of valuable information like planned working orders and maintenance optimization prediction.

The overall optimization considering the fleet management and external factors is not part of the LOCATE App, but this can provide information to support better decisions based on Remaining Useful Life (RUL) of the different components and maintenance operations optimization.

## 6.2. Operational Context

This section focuses on explaining the FGC maintenance scheme, which is currently in use for their maintenance operations, and changes that could be the potential first steps into its redefinition implementing predictive maintenance practices. This scheme is applied in the Locomotive 254.01, the one used for sensorisation and analysis in the LOCATE project (Figure 6).


Figure 6. FGC Locomotive 254.01

Railway undertakings make large investmentsw in rail systems, which must meet strict requirements in terms of Reliability, Availability, Maintainability and Safety (RAMS), over their whole life cycle. The European Standard EN – 50126 provides with a common process throughout the European Union for the specification and demonstration of RAMS requirements. Railway RAMS is a major contributor to the quality of service in railways, and it is defined by several contributory elements.

As many ECMs schemes, FGC Maintenance Scheme has been designed considering the available technology in the moment of the implementation and the context of the service, always in line with the RAMS requirements. Hence, it can be noted (as in previous LOCATE documents) that the lack of sensoring leads to many inspections with a significant amount of time in which no defect is found. While this is strictly necessary in order to ensure high RAMS indicators, the addition of sensors in critical components could reduce these inspection hours and improve the quality of the work carried out by maintenance professionals.

Additionally, it is important to highlight the company culture created when a maintenance scheme is implemented and carried out for years and decades. When designing new processes that involve new technologies and procedures, these must take into account the context and perspective of the ECMs and hence include the behavioral changes needed in order to implement them in an adequate manner, considering that, in cases where a scheme has been carried out for a long time and with a good performance, usually, the changes are realised in a more convenient manner when planned in small steps to be applied gradually.

### 6.2.1. Use case maintenance scheme

Maintenance is the combination of all technical and administrative actions, including supervision, intended to retain a product or restore it to a state where it can perform a required function.

Within this definition different types of maintenance exists are detected, as shown schematically in Figure 7. Maintenance can be divided into two main differentiated types of actions: preventive maintenance and corrective maintenance.

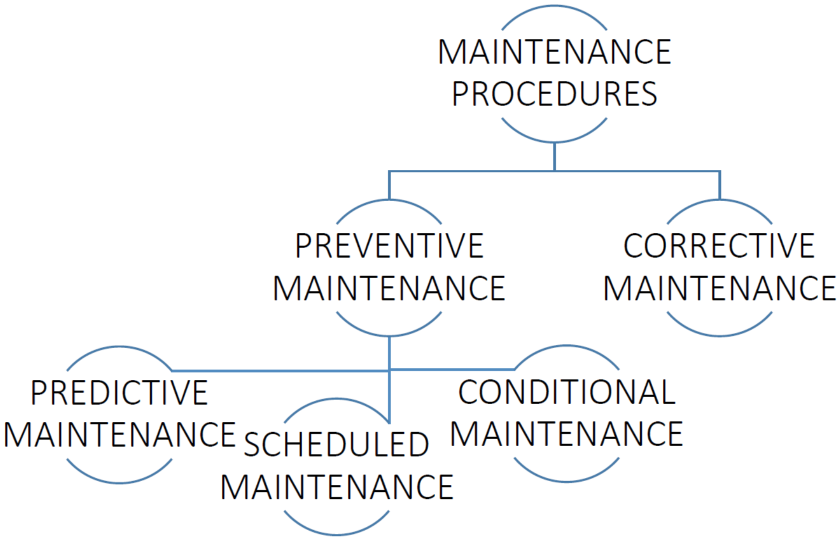



Figure 7: Types of maintenance actions

- Preventive maintenance is the maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.
- Corrective maintenance is the maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

Preventive maintenance can also be divided in three different activities: predictive maintenance, scheduled maintenance and conditional maintenance.

- Predictive maintenance is the maintenance done to elements, equipment, or systems that are monitored by means of sensors and software able to inform about future failures. Depending on the criticality of the alarm, the maintenance actions predicted may be scheduled or conditioned.
- Scheduled maintenance is the maintenance done according to a program previously established, where the frequency of the activities carried out is determined by units of use.
- Conditional maintenance is the maintenance triggered by previous actions like controls, tests, other maintenance actions like scheduled maintenance or predictive maintenance, diagnostics, measurements, etc.

It is important to note that all these types of maintenance actions come with a high number of documents, that are needed in order to apply the measures in a correct manner. In the case of freight locomotives, the documentation is usually less exhaustive due to the fact that the equipment of freight rolling stock is more basic than the one for passenger trains. In order to better reflect the amount of documentation associated with maintenance, a list of the most common documents and information is shown below:

- Components and equipment inventory.
- Drawings and schemes of all the components and equipment.
- General operating manual, including operation of all the components and equipment with recommendations of operation modes in case of failure.
- Preventive and corrective maintenance manual of the manufacturer with indications of: frequencies, inspection points, specific tasks, replacement materials, procedures, etc.
- Using this information combined with their experience the maintainer (FGC in this case) develops the preventive and corrective maintenance plans that will be used.

**LOCATE Demonstrator**

The addition of a predictive component into the current FGC maintenance system would allow to calculate and detect the degradation of components in advance and consequently schedule maintenance actions, either inside the scheduled maintenance plan or as correction actions based in the conditions of the components.

Scheduled maintenance consist of periodical inspections, actions, and specific tasks that try to prevent incidents during the operation of the system. FGC have a scheduled maintenance plan with a frequency based in the kilometers run by the rolling stock. Within these scheduled maintenance, there are some tasks that consist of observations, measures and monitor the conditions of specific components. This data is supervised in the technical office and some tasks that are programmed based in the conditions reported, which corresponds to the conditional maintenance.

Even when the procedures of preventive maintenance are as effective as they can be, during the operations, some incidents are detected. This information is reported to the workshop and some corrective actions are done. The most important idea with the incidences is that FGC have to ensure that the event detected does not affect to the safety or the availability of the locomotive because in that case the corrective action has to be done immediately having a direct impact in the quality of the service. FGC reports several incidents during service, butonly few of them really impact in the quality of service.

Considering FGC's perspective of the LOCATE project, there are two strategies that could optimize the current maintenance procedures and can impact positively in improving the quality of service:

- To monitor systems that could cause an immediate corrective action.
- To improve routinely tasks that consume resources.

FGC Rolling Stock department detected and proposed the following situations where predictive maintenance could improve the quality of the scheme, considering its experience with the maintenance procedures and day to day operation:

**Immediate corrective actions avoidance**

- Monitoring of bogie stability through the implementation of sensors (accelerometers) that are able to monitor the movement of each bogie, and also able to identify situations of upcoming derailment.

- Axle box monitoring with vibrations and temperature sensors able to detect any unusual values.
- Vibrations and temperature sensors for monitoring any unusual parameter of the electrical engines.

**Routine tasks strategy**

- Sand box level indicators.
- Brake shoes wear indicators.

The LOCATE developments have been tested in a real operational context within the LOCATE demonstrator in the FGC 254.01 locomotive, during the usual freight service, following the process depicted in Figure 8.

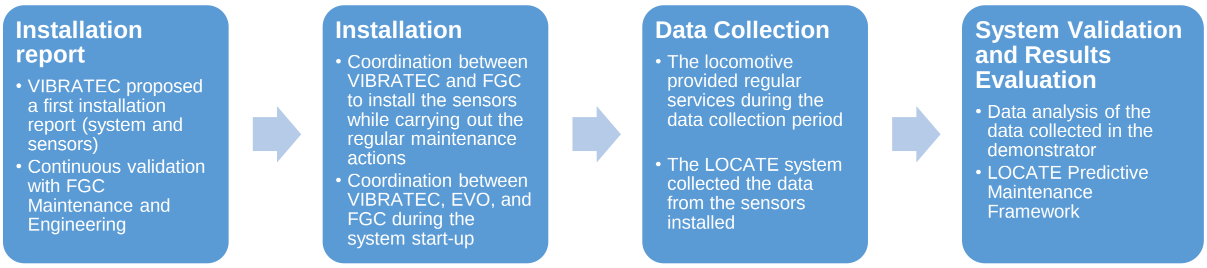



Figure 8: Workflow for the LOCATE Demonstrator

### 6.2.2. Impact of LOCATE on decision making

The following approach could be followed in terms of maintenance decision making considering the LOCATE monitoring as a support tool.

1. Defects that cannot be addressed via the LOCATE methodology. The corresponding maintenance to be done will be kept as it is.
2. Defects that can be addressed via LOCATE. In such a case, datasets are compared to offline assessments. iA warning is emitted when the sensor data processed by the correct algorithms compared to the results given by the digital twin show that a failure will occur. The rate of increase in the risk of failure may or may not be well known.
3. When the rate is not well known, depending on the consequences of the defect there are two possible positions.
    a. The risk in operation is acceptable: an inspection is organised as soon as possible. The repairs, when needed, are organised according to a timeframe corresponding to FGC's experience.
    b. The risk in operation is not acceptable: the locomotive is stopped as soon as possible.
4. When the rate is known and the remaining useful lifetime (RUL) before defect can be estimated, FGC organises the repairs.

5. If the repairs can be organised before the end of the remaining useful life, the locomotive is stopped when the repairs can take place, minimizing the impact on the availability of the locomotive.
6. If not, the locomotive is stopped before the end of the remaining useful life.

For a specific defect mode comparison of the results of inspections with those of the data with the processing of sensor data by LOCATE algorithms can lead to a refinement of our knowledge of the rate of increase in the risk of in-service failure.

For a specific fault mode, comparison of inspection results with those from LOCATE sensor data processing can refine our knowledge of the rate of increase in in-service failure risk and allow us to move towards purely predictive maintenance.

Today, the measurement time in operation and the sample size (one equipped locomotive) do not allow us to refine the RUL parameter for a given fault. But this could be organised by the ECM of the railway undertaker (RU).

### 6.2.3. Maintainers point of view

To define a maintenance scheme for a rolling stock being used in specific conditions of operation, adapting the first set of maintenance rules provided by the rolling stock provider we must consider

- Safety related issues: identifying the defect modes and their consequences in operation
- Needs of the customer (here, car manufacturer and mining companies.)
- Possible price of the service in the current state of the market.

Therefore, a balance between safety and availability of the assets has to be found. LOCATE was organised accordingly.

The following has to be done before changing the maintenance scheme of the FGC 254 series of locomotives.

The new maintenance scheme has to be as safe as the current one. It has also to increase to availability of the fleet.

Therefore, we have to apply the LOCATE measurements and algorithms and compare the results of these with the results of the inspections we continue to be done in parallel. This will help us to

- Demonstrate the accuracy of the LOCATE methodology for the defect modes on which it can be applied.
- Have a better estimation of the time between the detection of the coming defect via LOCATE and the estimate of the time made before a necessary repair made by the FGC maintenance team. For each defect we should then understand if FGC has enough time before the repair limiting the impact on the operations as much as possible by
  - Doing the repairs when it is possible
  - Preparing them, have staff, place in the workshop, parts in order to minimize the duration of the repair.

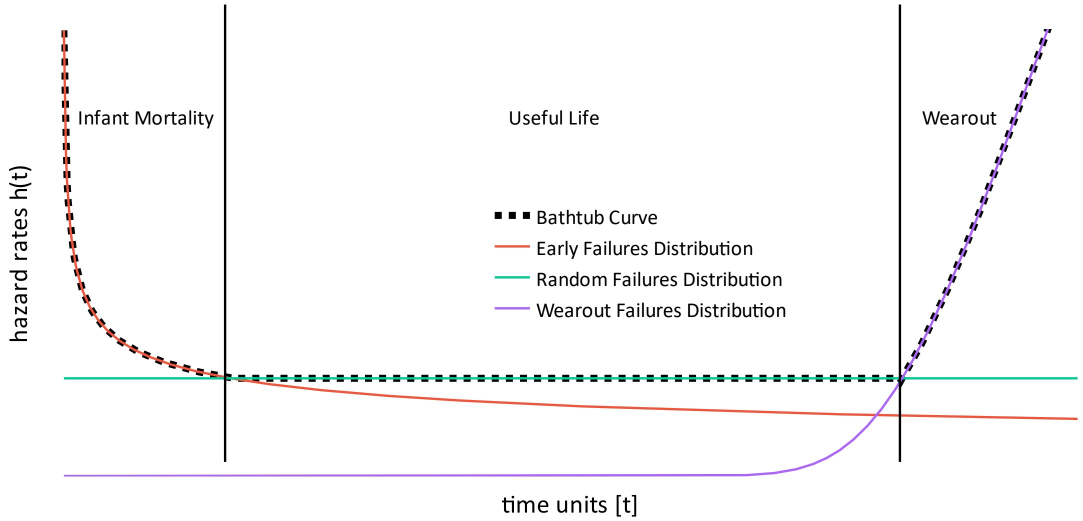
Currently

- A measurement system has been implemented on one of the three 254 locomotives of FGC.

- On line test have been made.
- A digital twin of the system has been created; its results compared with those of the digital twin
- A simulation tool to be used by FGC's fleet management has been provided.

In operation the defect hazard rates can be described in the following drawing

- After a part is replaced there maybe infant mortality
- After this first period; we have the period of useful life during with the defect rate is at a minimum.
- During the last period of time the probability of defect increases. The repairs have to be done before the hazard rate reaches a limit to be fixed depending on the consequences of the defect (see FMECA analysis provided earlier in the LOCATE project.




The main issue is to identify the time between the detection of a forthcoming fault via LOCATE and the moment when the risk of the corresponding fault occurring becomes unacceptable for the railway operator.

### 6.2.4. System Reliability

System's reliability is assessed based on the reliability and hierarchy of the subsystems, components and failure modes. Reliability Block Diagrams (example in Figure below of a k subsystems in series) can describe the hierarchy of such subsystems, and the reliability and availability relations between them. Given the complexity of these relation, the overall reliability and availability of the system is usually estimated by simulation. LOCATE project has developed a simulation procedure, using a Discrete Event Simulation (DES) model, to assess reliability and availability of subsystems of interest and of the overall system.

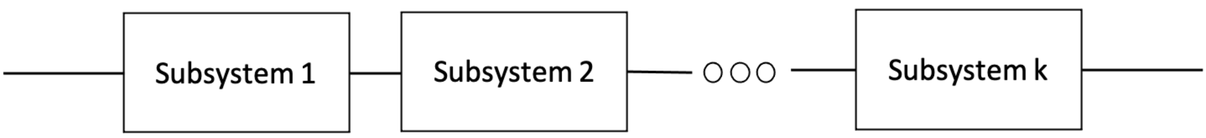



Figure 6-9: Reliability Block Diagram (RBD) of k subsystems connected in series.

### 6.2.5. Modelling RAM

In modelling Reliability, Availability and Maintainability (RAM) of the locomotive system in LOCATE, specific quantities of interest are monitored to predict the expected impacts of certain maintenance strategies, namely: i) Time to Repair (TTR) and the Time of Failure (ToF). Other delays are also included/considered [EN 50126]: undetected fault time, administrative delay, logistics delay, technical delay, and actual repair time.

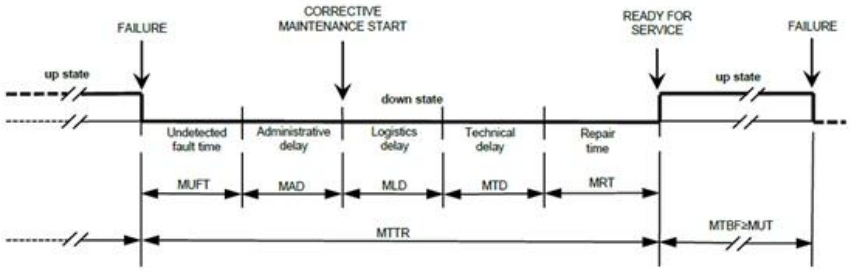



Figure 6-10: Sequence of times from failure to ready for service (source: EN 50126).

LOCATE sensors, for the selected failures modes, will eventually allow the reduction of the total Time to Repair, mainly through the decrease of delays (administrative, logistics and technical) and/or the elimination of the undetected fault time.

The main results, obtained using the DES model to estimate the associated reliability and availability of the system, provides an average availability of 89.7% of the overall system, with very high availabilities of the bogie frame system (99.991%). The simulation framework allows the inclusion of greater flexibility in the estimation of possible scenarios that can represent a wider range of different circumstances in operation, towards a robust assessment of reliability and availability of the system.

## 7. System Behaviour

This chapter presents an highlight of the approach on the different workpackages that runned in parallel to contribute to the system integration and test: Reference behaviour, Measured behaviour and Operational behaviour.

### 7.1. Reference Behaviour

The Reference Behaviour Work Package started by assessing the available models and several solutions were presented to study the degradation of bogie components using numerical simulations. Railway axle cracks can be detected by taking advantage of the periodicity of the fault signatures, which is related with the velocity of rotation of the axle. Several methods exist that allow the study of fatigue phenomena in railway bogies.

Likewise, various techniques exist that are already in use to monitor the condition of mechanical structures such as bridges and planes. However, to the knowledge of the authors, there is no published solution to monitor the bogie structure regarding fatigue. There is the potential for project LOCATE to fill this open point. A great number of solutions exist to assess the damage and degradation of suspension elements, both in the context of the modelling of the defective components, as well as the signal processing techniques for fault detection and identification.

Project LOCATE expects to contribute with more advanced models to represent body flexibility and damage, such as fatigue cracks in the railway axle and bogie frame. This was achieved using a flexible multibody formulation that employs modal reduction techniques to allow the efficient simulation of complex mechanical systems. Additionally, the degradation of suspension elements was analysed using multibody simulations, taking advantage of imperfect kinematic joints to allow a realistic representation of friction, local compliances, and clearances.

The computational model's specification was established and the suitability of the experimental data from the preliminary measurement campaign for the validation of the vehicle dynamics model of the Series 254 locomotive has been reviewed and compared to relevant standards. Whilst the measured quantities to not include information on wheel-rail forces typically used to validate vehicle models, the measured bogie frame and axlebox accelerations provided useful information to validate the dynamic response of the vehicle model. In turn, the validated vehicle model simulation, in normal operation conditions, delivers the normal dynamic response of the systems. By varying the selected boggie modelling parameters, suspension spring characteristics, boggie chassis crack locations and propagations, wheelset cracks, etc., vehicle abnormal dynamic responses will be obtained and related to KPI. Key Performance Indexes (KPI) were determined from post-processing of the measured quantities and used to support model validation and component condition classification. These KPIs include statistical quantities associated to the dynamic responses, such as standard deviations, maximum and minimum accelerations, relative displacements of the boggie components, etc. The systematic use of the simulation tools to analyse all the possible combinations of modelling parameters is unfeasible, as each simulation may take from several minutes to several hours, depending on the operation conditions, extent of the track covered by the vehicle and on other interaction conditions. Therefore, the use of a meta-models to estimate the vehicle response as a function of the health of the bogie subsystems has been introduced. A range of Design of Experiment techniques have been identified to estimate reliable metamodels and will be applied during Task 4.4 to develop the Digital Twin. The decision is to define the DoE based on the Latin Hypercube Sampling and the metamodel based in Kriging.

The models were developed, and the methods implemented to evaluate the condition of bogie components using dynamic simulations. The results of multibody simulations represent the nominal and abnormal response of the vehicle, providing a database of the locomotive reference behaviour. This database supports the identification of the health of the bogie components. The failure modes addressed in WP4 are cracks in the bogie frame and wheelsets, and the degradation of elements in the primary suspension. Condition assessment is accomplished using damage detection methods based on the transmissibility concept, such as the Transmissibility Damage Indicator (TDI) and Maximum Occurrences (MO) methods. The degradation of primary suspension elements is also assessed using surrogate modelling. The main conclusions of the research activities can be highlighted:

- A static analysis based on standard EN 13749 was used to define an appropriate location for a crack in the welded connections between the front transversal beam and the side frames. The lateral accelerations measured at selected points in the bogie frame were obtained from a set of simulations of the vehicle-track interaction considering different crack sizes and a constant speed of 60km/h. The transmissibility matrix of the measured response is computed in the frequency range of 10-150Hz, and the results show the TDI method is sensitive to damage if the crack area is at least 63% of the cross-section of the welded connection. Further increasing the crack area reduces the TDI value. The symmetric and non-symmetric schemes used to compute TDI suggest a threshold of 0.7.
- The results from the flexible multibody simulations rely on the sensitivity of the natural frequencies and vibration modes of the structure to the existence of damage. The modal analysis of the wheelset shows the natural frequencies are only sensitive to cracks perpendicular to the axle if their depth is higher than 25% of the axle diameter. Therefore, this method is unlikely to detect damage in the wheelset before the crack grows exponentially.
- The TDI method can measure changes in transmissibilities caused by damage in the primary suspension. It is sensitive to a 50% reduction of the nominal value of spring stiffness and a 40% increase or decrease of the nominal value of the damping coefficient of the viscous damper. TDI is sensitive to damage in the primary suspension given the sources of variability in the simulations, i.e., track irregularities, speed and uncertainty about the nominal values of the mechanical properties.

- After detecting damage in the bogie frame using the TDI method, the MO method identifies the entry corresponding to the highest difference between the nominal and measured transmissibility matrices. The indices of this entry correspond to the pair of sensors detecting damage. The sensitivity of the MO method depends both on the frequency range considered for the response and the position of the sensors. However, when damage is detected on springs it can only indicate if the damaged spring is in the leading wheelset or on the other two. The method cannot isolate damage in the middle and rear wheelset.
- Surrogate models of the standard deviation of the lateral acceleration of the bogie frames show good fit, low absolute percentage error, and sensitivity to spring damage. The stiffness values used in the simulations range from 10 to 190% of the nominal stiffness. However, it is not clear what values are acceptable before the spring can be considered damaged. Upper and lower stiffness limits were defined for discrete speed intervals based on the variance of the surrogate. Finally, the maximum and minimum of the surrogate within the stiffness limits constitute the threshold for the response.
- A Recursive Least Square method for the estimation of the primary suspension parameters is presented. The RLS method is suitable to monitor the condition of suspension systems that can be represented by linearised models. Since this RLS method is based on the parameter estimation with Input-Output model, the estimation result is not sensitive to the operational condition.

The following diagram captures the data flow and condition monitoring methods researched.

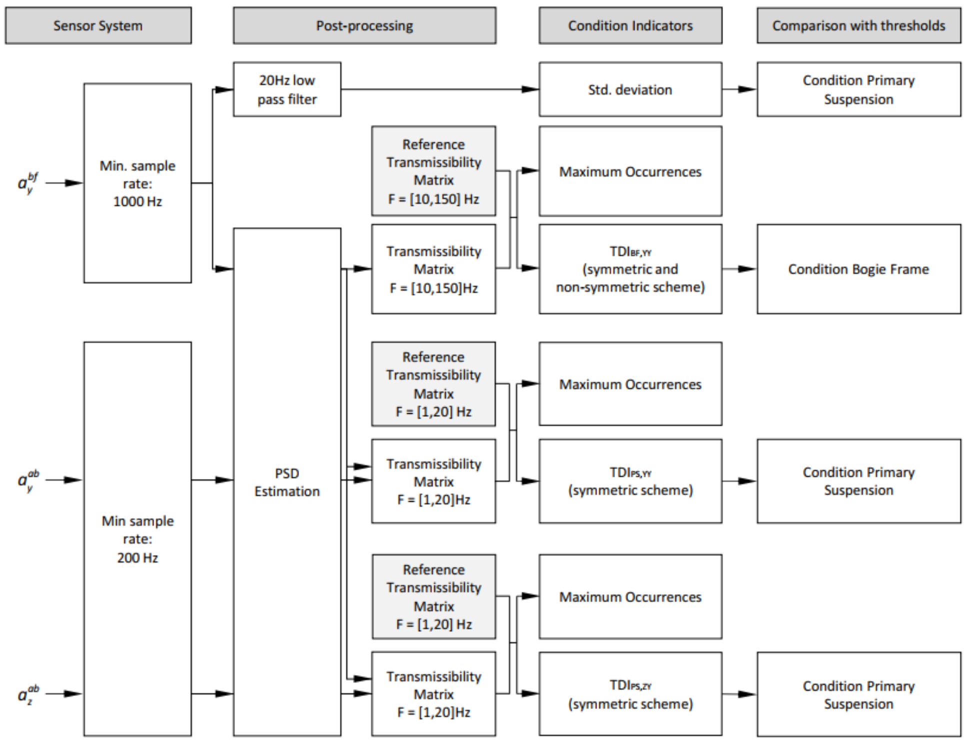



Figure 7-1: Condition Monitoring Thresholds computation

## 7.2. Measured Behaviour

The WP3 started by performing an assessment of the available technologies in terms of sensors and monitoring approaches and organized an initial measurement campaign to support and evaluate the sensors selection. Additionally, an important knowledge was used from previous experience from industry leaders in a LOCATE Advisory Board Meeting, including members from Shift2Rail Project FR8Rail III.

The outputs from this first measurement campaign provided the data to allow this evaluation to take place, prior to selecting the sensors for use on the longer-term measurement campaign.

The post-processing resources and adequate on-board computational resources were also adjusted in function of the field experience acquired during the first measurement campaign and work supply by the different work packages.

Initial statistical and frequency analysis of the measured data suggests that the selected sensors and sensor locations provided useful information for the monitoring of bogie stability (low frequency accelerometers) and detection of abnormal behaviour in suspension and wheelset (profile related conicity issues) components of the bogie system. Measurement of high frequency accelerations has been shown to provide useful information on the performance of the axle box and with future post-processing could be used to detect abnormal behaviour of related components, such as bearing, wheelset (tread defects) and gearbox.

The data acquired during the preliminary measurement campaign was used to validate the dynamic response of the computational model in WP4 and support the development of the Digital Twins.

Overall, the preliminary measurement campaign was a success. It shows the ability to instruments the locomotive with all the necessary sensors to address the different use cases defined in the project.

The different sensors have been evaluated and an informed choice was undertaken for the longer-term measurement campaign depending on the strategies defined in WP4 and WP5.

This preliminary measurement campaign has also helped to define for the specification for the longer-term measurement campaign and integration of the LOCATE system, for example powering, wires, and hardware integration.

It showed also that monitoring the global status of the locomotive is important: velocity, currents, curve radius., as the measurements should consider the different conditions of the track, operating speed or load. Instantaneous wheel speed is highly important especially when GPS is lost. The signal from odometer already installed on the wheel of the locomotive would provide a more precise and robust measurement of speed.

A proposed strategy employed in the full measurement system was to enter the vehicle into a diagnostic cycle at given periods when the locomotive is within prescribed operational boundaries.

This will require prior available coordinate system maps of stations and points of reference when the vehicle will normally enter a diagnostic zone. The zone will be controlled by factors such as speed, GPS location, loading conditions and any other parameter that can establish baseline measurements from which critical repeated measurement for the failure modes will be recording by the monitoring system. A register will be kept for the baseline measurements from which thresholds by measurement will also be stored.

## 7.3. Operational Behaviour

The Operational Behaviour Work Package started by the identification of operational constraints and non-negativity restrictions associated with bogie maintenance. Typically, these consist of technical (e.g. associated with the type of locomotive, depot layout and capacity, resources and spares inventory) and non-technical constraints (e.g. personnel, depot management, competence/skills and working conditions). The general maintenance instructions, programs and failure records associated with freight locomotives and the actual maintenance practices at the FGC depot have been reviewed. The key constraints related to the maintenance of locomotive have been identified and summarised in this deliverable. These include a mixture of:

- Operational constraints – business model of FGC, service requirements, depot management, resource requirements and spares inventory policy
- Technical constraints – type of locomotive, regulations/requirements of maintenance related to the select component/sub-system
- Economic constraints – specific budget of maintenance

Although there are some variations in the maintenance planning due with the constraints of different international rolling stock maintainers; the adoption of international standards and interoperability means that they are similar.

The current maintenance regime for the FGC Series 254 locomotive has been reviewed to identify the specific constraints and dependencies for selected use cases. The current regime focuses on the safety and availability of the locomotive and includes the replacement and repair of components off the vehicle. This makes the planning of spares more important, especially when moving to a CBM approach (where components may be in-service for a longer period). Examples of typical maintenance threshold/rules and resulting maintenance activities have been provided.

Finally, specific data requirements have been identified which will support the definition of objective functions to describe these constraints for inclusion in the maintenance decision framework during the WP5 of the LOCATE project.

Currently, FGC adopts an on-condition based maintenance regime, where inspections are undertaken and specified intervals with defined thresholds. If one of these limits is reached an intervention to correct the problem should be made as soon as possible. The LOCATE project proposes to replace this with a predictive maintenance system for the bogie of the FGC's locomotives. This system will continuously monitor the bogie and the performance will be compared to reference data obtained from a digital twin. Failures will be anticipated and the time before the failure affects the locomotive operations shall be estimated, based on the defined thresholds and rules. The scheduling of this operation (D5.3) must be done to limit the impact on the availability of the fleet.

To define the threshold and rules, it is initially proposed that the failure rates defined in the FMECA (WP2) and/or manufacturing data (if available) are utilised to provide the most accurate representation of the failure rates of the components (accounting for any variation between components/operation). These should be combined with the condition data to provide an estimate of RUL. These can be combined with the operational constraints, from D5.1, to support the condition maintenance framework (D5.3). The failure rates should be reviewed during long term measurement campaigns in collaboration with FGC and provide feedback on the accuracy of the LOCATE system.

Definition of thresholds and rules, such as the P-F curves, depend on the system/component being assessed, failure modes and type of data monitored. In the LOCATE system, the measured and reference behaviour provide an indication of the health status (or performance) of the system/component. Thresholds/rules are required to provide an indication of when maintenance is required, with sufficient time for maintenance to be scheduled based on the health status of the system/component. This requires an understanding of the relationship between performance and degradation to support the prediction of the estimated-time-to-failure (or RUL) and definition of the P-F curve.

The type of thresholds used is dependent on the type and format of measured/reference behaviour data. For example, data could include physical measurements of the actual condition of a component/system (e.g., wear measurement of a wheel profile) and sensor data (e.g., vibration measurements) which require some form of post-processing to infer the component/system condition or functional performance. If the physical condition of the component/system is monitored, then changes in the measured data can be tracked to detect potential failure which can be linked to industry (safety) and company (performance) limits. In the latter case, features in system performance, e.g., peak frequencies which change with degradation (e.g., symptoms) need to be identified and there are challenges in terms of identifying the type and severity of a fault and recommending the most appropriate maintenance action.

To support the definition of initial thresholds and rules in the LOCATE project, existing standards and techniques for condition monitoring and prognostics have been reviewed. Techniques, such as failure mode symptoms analysis, were shown to provide useful information for identifying the symptoms which potentially lead to a particular failure, the current means of detection and thresholds which trigger a maintenance action. In discussion with FGC and the LOCATE Advisory Board, this technique has been applied to each of the selected use cases to link the main failure modes identified in the FMECA developed during WP2 (D2.3) with the symptom(s) and proposed measured or reference data.

The expanded FMECA includes details of the current detection method and existing (or typical) thresholds and rules that are applied to each of the use cases. In LOCATE, these will be replaced with information (either physical measurements or data features) from the measured or reference data developed during WP3 and WP4.

An estimate of the P-F interval, in time or distance, for all the identified failure modes would have been a valuable addition to the FMSA. However, in the current preventative maintenance regime adopted by FGC, the failure modes are not permitted to remain in the system past the potential failure point (P). This concept is not natural in the current regime therefore no records of extending RUL or scheduled maintenance intervals exist. It is envisaged that once the CBM system is in place and the maintenance transitions to a PdM regime, failures modes will be tracked more closely and a better understanding of the limits and threshold to support the confirmation of the initial P-F intervals defined in D5.3.

The main goal of tasks 5.3 and 5.4 was to deliver a framework, in the context of bogie maintenance and compatible with current FGC's maintenance practice and standards, for decision-making support and optimisation of maintenance plans. In particular, the optimisation tool should be flexible to incorporate changes related to the acquisition of sensor information.

The key constraints and variables to the maintenance of the locomotive or, more specifically, the operational constraints defined on deliverable D5.1 and the monitoring thresholds and decision support rules defined on deliverable D5.2, were used and a simulation experiment was first proposed to assess the impacts of having models with different configurations and failure patterns for the various bogie's subsystems. The optimisation-based framework was constructed after the appropriateness of the main assumptions, including failure rates, were tested in the simulation model.

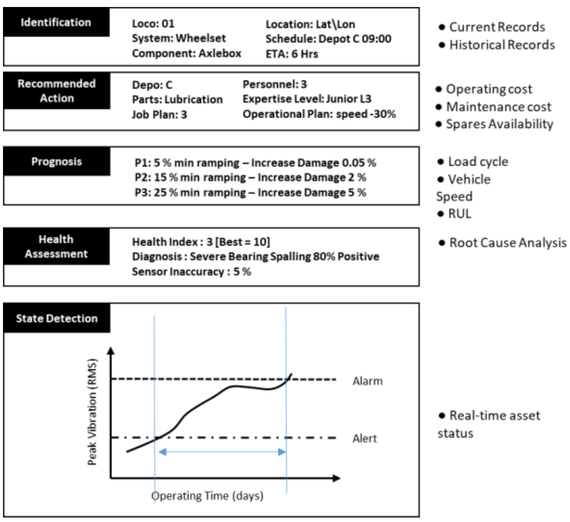



Figure 7-2: Optimization framework

Although sensor information was not available at the time this activity was performed, a sample problem using simulated data was proposed to test the optimisation algorithm. The results showed good suitability of the model to capture the main characteristics of the current maintenance FGC's practice and, on top of that, to serve as a decision-making support tool to define short-term and long-term changes to the maintenance scheme, especially when sensor information is available.

# 8. System Integration and Validation

This chapter presents the integration and validation results.

## 8.1. Measuring points

Regarding the WorkPackage 4 main results concerning the edition of indicators using the correlated referenced model, the instrumentation is mainly made by accelerometers distributed on the bogie frame and axle boxes.

A total of 19 vibration channels are distributed on the bogie frame and the axle box on 19 degrees of freedom (DOF) : 14 DOF are on bogie frame side and 5 DOF are on the axle box.

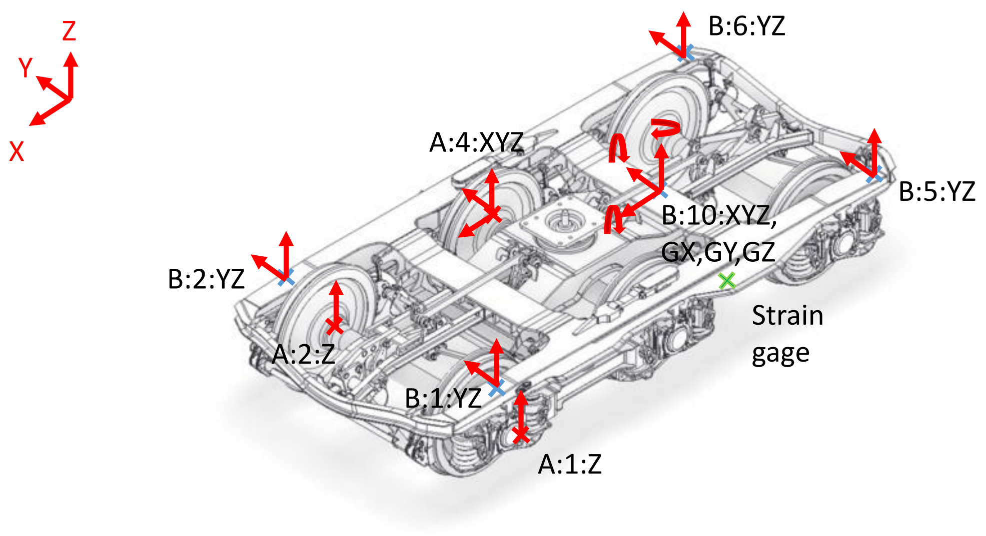
There are:

- 4 bi-axial accelerometers on each corner of the bogie frame in Y and Z directions,
- 1 inertial measurement unit in the centre of the bogie frame measuring the 6 DOF,
- 1 triaxial accelerometer in an axle box equipped with a damper,
- 2 mono axial (Z direction) accelerometers on the front axle box.

The first figure presents the distribution of these 19 DOF on the bogie frame and the axle box.

The second figure presents the exact position on the exact bogie frame of the locomotive.

Finally, the following table presents the measurement name and corresponding frequency sampling.



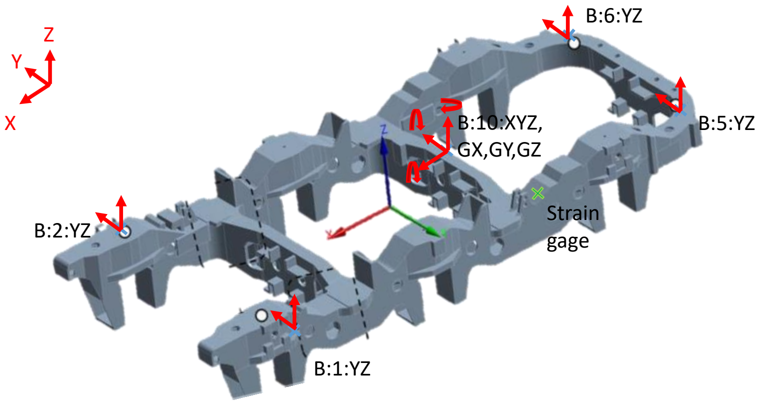



Figure 8-1 : Measuring point

| NAME | UNIT | Frequency sampling |
|---|---|---|
| B1Y | m/s^2 | 2 kHz |
| B1Z | m/s^2 | 2 kHz |
| B5Y | m/s^2 | 2 kHz |
| B5Z | m/s^2 | 2 kHz |
| B2Y | m/s^2 | 2 kHz |
| B2Z | m/s^2 | 2 kHz |
| B6Y | m/s^2 | 2 kHz |
| B6Z | m/s^2 | 2 kHz |
| AB4Y | m/s^2 | 2 kHz |
| AB4Z | m/s^2 | 2 kHz |
| AB4X | m/s^2 | 2 kHz |
|  | A | 200 Hz |
|  | A | 200 Hz |
|  | A | 200 Hz |
| AB1Z | m/s^2 | 20 kHz |
| AB2Z | m/s^2 | 20 kHz |
| TEMP_AB1 | °C | 20 Hz |
| TEMP_AB2 | °C | 20 Hz |
| STRAIN_GAGE | µm/m | 2 kHz |
| Temp_demo_box | °C | 10 Hz +/-1Hz |
| Temp_ambiant | °C | 10 Hz +/-1Hz |
| B10Y | m/s^2 | 500 Hz +/- 1Hz |
| B10Z | m/s^2 | 500 Hz +/- 1Hz |
| B10X | m/s^2 | 500 Hz +/- 1Hz |
| B10RY | °/s | 500 Hz +/- 1Hz |
| B10RZ | °/s | 500 Hz +/- 1Hz |
| B10RX | °/S | 500 Hz +/- 1Hz |

| NAME | UNIT | Frequency sampling |
|---|---|---|
| Longitude | | 5 Hz +/- 1 Hz |
| Latitude | | 5 Hz +/- 1 Hz |
| Altitude | m | 5 Hz +/- 1 Hz |
| Velocity | km/h | 5 Hz +/- 1 Hz |
| Direction | ° | 5 Hz +/- 1 Hz |
| Distance | m | 5 Hz +/- 1 Hz |

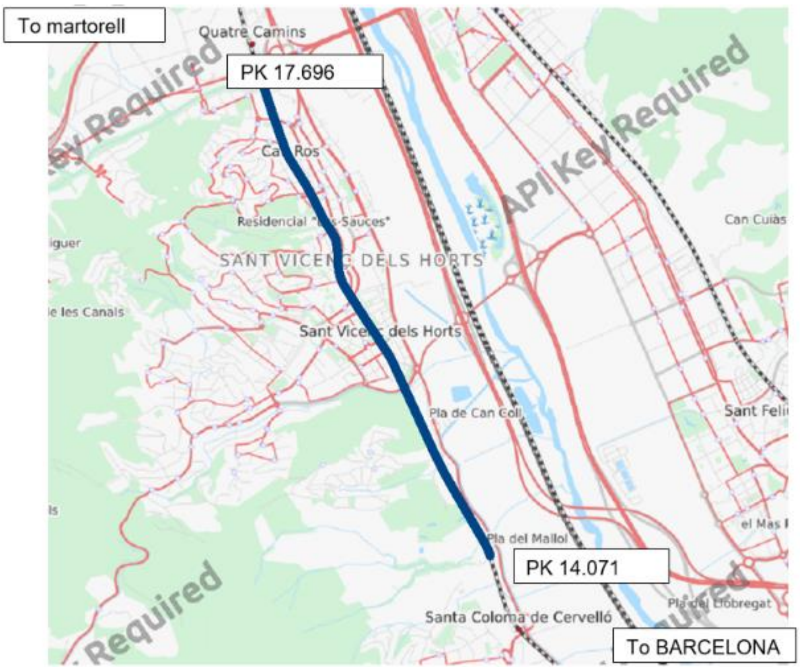
Table 8-1 : Frequency sampling in function of measurement name

## 8.2. Section of recordings

The selection of the track sections followed the following criteria:

- Track section adequate to correlate with IST simulations.
- Good GPS reception.
- Same sections used for preliminary data.
- Relevant load conditions are depend of the sub system to monitor :
  - gearbox and electrical engine : current should be upper than 150A with a stabilized speed.
  - Axle box : no load on electrical engines (0A) and stabilized speed
  - Wheel flat : no load
  - Electrical engines : detect unbalanced current between 3 engines necessitate to check when current is required
  - Bogie stability : the referenced model is not available to determine the most influence parameters but locomotive speed intervals will be defined in order to be reproducible.
- Engine performance conditions
- Geometric data available

The retained sections are illustrated in next figures.



- Barcelona-Martorell : PK 14.071 to 17.696 duration 225s to 350s distance : 3.625 km

  **Zone to wake up** (system on power saving mode)

  - 41.363071<GPS<41.42982244
  - 1.9941<GPS<2.03243

  **Zone to measure**

  - 41.37476<GPS<41.404322
  - 2.002572<GPS<2.02154


Track conditions :

- Suria/Manresa : PK 8.446 to 4.143, duration 400 to 450s, distance : 4.303 km

  **Zone to wake up**

  - 41.761987<GPS<41.79703
  - 1.7759207<GPS<1.826028

  **Zone to measure**

  - 41.76082705<GPS<41.78877739
  - 1.782184<GPS<1.81121265

The retained sections for model correlation seems to be a good choice in terms of conditions that are representative of the full track. Indeed, there is a good mix between load / no load on electrical engines, vehicle speed conditions (around 50 to 60 km/h on straight line and 30 to 40 km/h in mountain), there is curved or straight line, the roughness of the rail appear in a good condition (looking at the axle box acceleration).

The sections should not include tunnel in order to have a correct GPS signal used as a trigger for the data acquisition and distance measurement.

## 8.3. Data collection

The system runs during one month and data were collected during this period.

The data collection is given in the following table. A total of 29 runs are recorded on the sections.

| SECTION | Number of runs | Avg speed (km/h) | Max Speed (km/h) | Avg Current (A) |
|---|---|---|---|---|
| Manresa to Suria | 5 (+2) | 40,8 | 35-44 | 74,8 |
| Suria to Manresa | 6 (+2) | 38,3 | 37-39 | 106,4 |
| Martorell to Barcelona | 10 (+3) | 47,3 | 37-67 | 31,6 |
| Barcelona to Martorell | 8 (+2) | 53,8 | 38-64 | 108,6 |

Table 8-2 : Number of runs obtained per section

Due to low power device problems on relay and internal error, battery power were loose at the beginning of the measurements.

Additional runs were obtained at the end of the project, data were not transferred before the end of 4G subscription. These runs are noticed in brackets because they are not used in the following analysis.

## 8.4. Measurement Analysis

The measurement analysis started by some statistical analysis to detect any abnormalities on the data and to have a better description and understating of the data characteristics.

The first approach was to detect if all the measurement run on a same section have the same total distance done by the locomotive. Using the total distance helps to detect abnormal recordings. When the section has a reduced total distance, it is because the measurement start after the first GPS trigger and then stopped recording by some reason.

It was also observed, that depending the load of the locomotive, the locomotive speed and current consumption can be very different for a same section.

A waterfall of Power Spectra Density (PSD) of acceleration measured on the bogie was computed and current and rotational speed of the bogie (Gyro Z) is plotted in parallel.

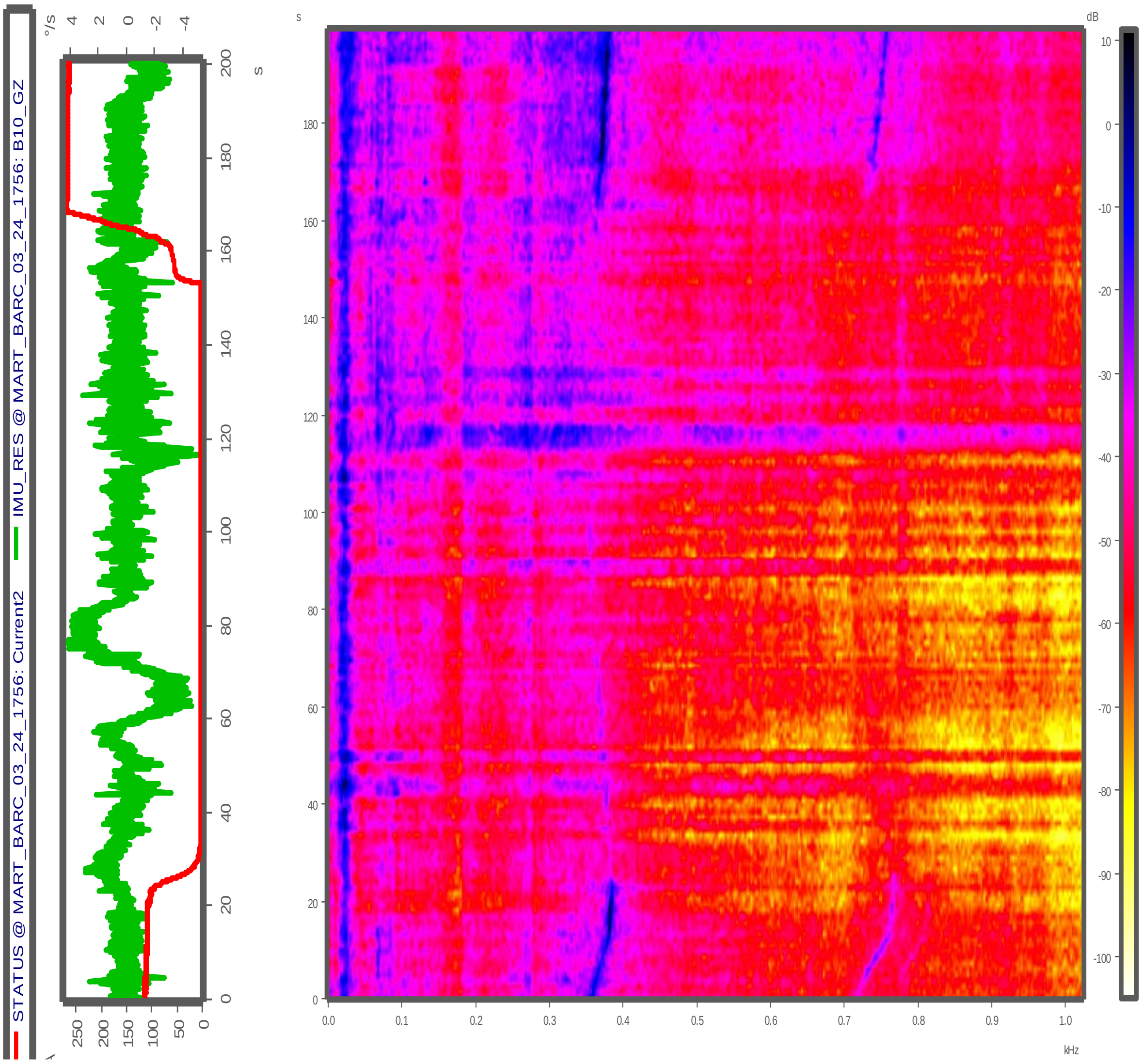


*Figure 8-2 : Waterfall of power spectrum density with moving window and linear averaging of 10 spectrums on 200s of* signal on section Martorell to Barcelona. Time signal of current and rotational speed of bogie frame on left.

The previous PSD waterfall shows an important variation of the PSD in function of time. This variation are due to current consumption and appearance of gear box excitation on the bogie and track irregularities.

The averaging time to compute the PSD that represents the averaged vibration behaviour of the bogie should be long enough to smooth the effect of the track irregularities and operational condition of the bogie.

Taking a longer averaging time allows to smooth the variation of load and track irregularities and converge to an averaged vibration level. The effect of load on the locomotive generates more vibration due to gearbox vibration between 300 to 400Hz.

A strategy should be to compute PSD only when current is 0 Ampere in order to remove gearbox excitation to focus only on bogie vibration response. Or to computed PSD only when the current consumption is a certain level in order to focus on the gearbox excitation.

It was also observed that the vibration levels measured on all the sections are very similar, 5 to 10dB of variation on all the 38 runs for a same measuring point.

On this locomotive, the decoupling frequency between axles and bogie frame are:

- 30Hz in Z direction,
- 50Hz in Y direction.

When comparing the dependency of the vibration levels to the track section of the measurements, it was observed:

- The PSD profiles are different between axle box 1 and axle box 2 but there are very similar for the 4 different sections of track. One profile is 8 dB lower on the entire frequency band. This lower level is measured on section Martorell to Barcelona which have an averaged current 2 to 3 times lower than the 3 others. It means that the vibration profile is mainly made by local response of the axle box and load on the electrical engines. The averaged PSD on 200s of signal on axle box in Z direction is not dependent of the selected section.
- The same analysis is done on bogie frame in Z and Y direction (on point B5). The PSD is presented from 0 to 250Hz for the 4 sections. In the Z direction from 10 Hz to 80 Hz, the vibration levels are mostly due to rigid body motion and natural frequencies of the bogie frame. But below 10Hz, the track irregularities due to the section explain the differences in terms of vibration level. In Y direction, the PSD levels are mainly made by the section type and there is no common profile due to only bogie frame modal response.

When comparing the measurement dependency between locomotives, since the preliminary measurement campign was performed on a different locomotive from the one used for the final validation, and some sensors and positions are very similar.

Frequencies are characteristic of rigid body modes of the bogie frame on primary suspensions and first bending modes of the bogie. It characterizes mostly the bogie system and it appears to be independent of the locomotive serial number.

The edition of PSD profile in Z direction can be a good and simple indicator to detect abnormal situation in terms of bogie stability or emergence of a new excitation due to wear on gearbox or flat on a wheel.

The same analysis is done using the acceleration measured in Z direction on the 2 front axle box and the accelerometers are much more sensitive to the sub-system and also to the measuring point location.

Indeed, on point A1Z the axle box is not equipped with the same odometer on the 2 locomotives and then the dynamic response at this point is very different between the 2 locomotives

On B2Z axle box, the sub systems are the same, but the accelerometers were not glued at an identical location. The PSD profile at high frequency can be significantly different in function of the point location.

PSD indicator on axle box can be use only to monitor the instrumented bearing and generic profile cannot be edited to use for all the axle box of a same type of locomotive.

### 8.4.1. Use of PSD and transmissibility as indicators

The definition of a standard PSD profile on bogie based on the measurement of 10 first operations on the section can be develop in order to detect abnormal situation on the locomotive as:

- Flat on the wheel: it generates an important level of vibration at each turn of the wheel. It will increase highly the vibration level on the bogie.
- Increase of gear box excitation level due to gear mesh wear or misalignment can also be detected by putting some threshold on a certain frequency band of interest.

The definition of a PSD profile on vibration measured on a bogie can be done with the following recommendations:

- 200s of signal minimum,
- Gyroscope measuring range from +/- 20°/s maximum,
- Frequency band from 0 to 1000Hz for accelerometers,
- Knowledge of locomotive speed and current consumption (or torque on engine)

The measurement on axle box in Z direction can be useful to monitor a bearing by following the RMS level on a specified frequency band of interest (5 to 10kHz) but this indicator should be sensitive to sensor position and locomotive configuration. It is mostly convenient to follow one specific component but not really easy to deploy on a complete fleet by the operator.

The acceleration signal measured on the axle box is mostly convenient to describe the track/wheel contact and normalizing the excitation levels and detect abnormal track irregularities. It is also a key indicator to identify easily the rigid boy modes of the bogie on primary suspension.

But the addition of a sensor on axle box is not an easy task on retrofit and is exposed to very harsh conditions (water, ballast) and generates new constrains on maintenance of the axle box itself.

The PSD profile is a good strategy to detect abnormal vibration due to a new source of excitation as a flat on the wheel.

The WP4 presented the use of transmissibility instead of PSD to detect modification on the system and avoid the effect of external excitation and interaction with the track on the indicator.

The Transmissibility Damage Index was computed using calculation and measurement signals. Some Frequency Response Functions (FRF) were computed between different measuring points of the bogie. The use of FRF can help to converge to system response by normalizing the vibration level measured on a measuring point with a referenced channel.

## 8.5. Reference Model Validation

This section presents an extension to the results on LOCATE deliverable D4.3 to assess the reliability of the Transmissibility Damage Indicator (TDI) method to assess the degradation of suspension elements and the existence of bogie frame cracks. The results presented follow the same post-processing and sensor systems considered in the deliverable D4.3.

It was evaluated the impact of the vehicle speed on the TDI values obtained for the condition monitoring of the primary suspension. For that purpose, the simulated vehicle response in nominal state and the on-track measurements, corresponding to the locomotive after a maintenance action, are used. The analysis does not intend to combine the signals simulated and those from the on-track measurements to calculate the TDI, but rather to evaluate if the effect of speed is consistent in the two cases.

The simulations signals used correspond to the locomotive running at constant speed for 100s in a straight track with real irregularities. The locomotive is at nominal condition, accounting for a 10% variation of the suspension parameters to consider the operation variability. Therefore, each simulation, that correspond to a vehicle speed, differs from the others to up to 10% of each of the spring/damping coefficients of the springs and dampers of the primary suspension.

It was observed that regardless of the combination of speeds, the TDI values are considerably high. However, it also shows high TDI values for the biggest speed differences when comparing signals from speeds below 40 km/h to signals above to 50 km/h. This effect can be a result of the excitation of some rigid body modes of the locomotive when the vehicle is travelling below 40 km/h or above 50 km/h, however, this requires more research to be confirmed.

In general, the results show some resilience to the 10% uncertainty on the primary suspension parameters by showing consistently high TDI values. Depending on the calculation of TDI using the lateral or vertical accelerations, different speed ranges might be considered, in order to ensure high TDI values when the locomotive is in a healthy condition.

The on-track measured data is now used to assess the impact of the speed differences in the calculation of the TDI. It is important to stress that the measurements were performed immediately after a maintenance action, decreasing the chances of damage or failure during the period of measure. To perform the analysis, nine measurements of the locomotive running between Martorel and Barcelona are considered. The measured signals have approximately 190s. Since the locomotive travels at variable speed during operation, the average speeds were obtained for each measurement and are used as reference for comparison of the different speed scenarios. In addition, there are other differences between measurements that are inherent to the railway operation, such as the tractive effort and the number of pulled wagons. Nevertheless, the interest of performing this analysis is also to evaluate the resilience of the TDI to these sources of variability

It is observed that the TDI values tend to be higher when the TDI is obtained using two sensors rather than four. Nevertheless, the TDI values are generally high, with some exceptions that would require further research to be fully understood. It is also not observed any specific trend, suggesting that the TDI using the vertical accelerations is not very sensitive to the speed differences.

The TDI values when using the transmissibilities between the lateral accelerations at the axle box and bogie frame are, again, generally high and shows a good agreement between the on-track measurements and the simulated response evaluated in the previous section.

In conclusion, the TDI method shows some resilience to the uncertainties and variability inherent to the railway operation, by providing high values when the locomotive is running at nominal conditions and for the different running speeds. When using the transmissibilities between the vertical accelerations, the results show a small effect of the speed differences in contrast to a pronounced effect of these when using the transmissibilities between the lateral accelerations.

It was also assessed the impact of the length of the signals used for the calculation of the TDI. For that purpose, simulations of the locomotive running for 200s at different constant speeds are used. The TDI values are obtained by comparing the signals corresponding to the vehicle in a similar nominal state. The results clearly show that the TDI values increase with the length of the signals. The results also show that the TDI calculated with the vertical accelerations is more sensitive to the differences in the track irregularities than that using the lateral accelerations.

A similar investigation is performed using the results of a single simulation concerning the bogie frame condition. The simulation involves the locomotive running on a straight track with realistic irregularities at a constant speed of 60 km/h. The vehicle model considers the structural flexibility of the bogie frame in nominal condition and the relevant simulation outputs are the lateral accelerations measured by the virtual sensor network described in deliverable D4.3.

The results showed that, using longer time signals or longer track sections, TDI is less sensitive to external perturbations such as differences in the track geometry and track irregularities. On the contrary, the TDI values processed using shorter signals or shorter track sections are substantially lower, despite the bogie frame being in perfect conditions.

Measurements of longer time signals and longer track sections allow reducing the variability in the accelerations that is associated with external perturbations, such as differences in the track input, thus improving the sensitivity of the TDI method to damage. This result is true for the case concerning the assessment of the condition of the suspension elements, as well as the case associated with the structural health monitoring of the bogie frame.

It was also compared the TDI with the analogous to the Detection and Relative damage Quantification indicator, proposed by Sampaio and Maia [1], using the symmetric scheme and the damage case described in detail in LOCATE deliverable D4.3. The results show that DRQ is consistently more sensitive to damage than TDI. However, preliminary results, show that DRQ is also more sensitive to external perturbations, such as differences in track sections. Still, both methods fail to detect the case of a crack with 20% cross-section area of the transversal beam. It is also worth noting that the TDI and DRQ methods require exactly the same type of reference and measured data to compute a damage index. Further research is required to assess in detail which of the two methods is more adequate to detect damage.

## 8.6. LOCATE Software Frontend

The LOCATE App is based mainly in two dashboards, the first for an end-user interested in a near real-time notifications for decision support in a short time frame (e.g. train driver, service planner or high priority maintenance intervention reaction needed). The second dashboard is for maintenance decision support.

The interface to the 3rd Party Software is to enable the integration of valuable information, such as planned working orders and maintenance optimization prediction.

The overall optimization considering the fleet management and external factors is not part of the LOCATE App, but this can provide information to support better decisions based on RUL of the different components and maintenance operations optimization.

### 8.6.1. Users Authentication

The following picture is a screenshot of the LOCATE App user login.

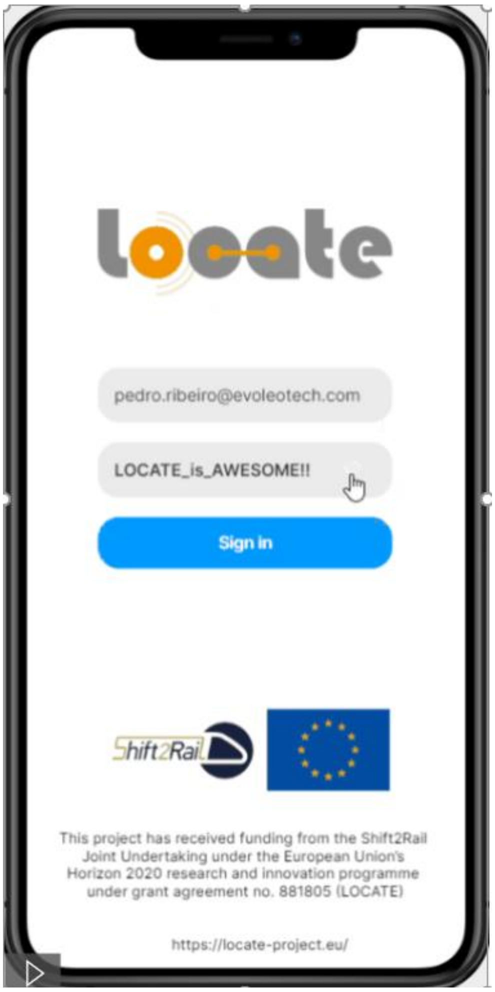



Figure 8-6: LOCATE App User Login screen

### 8.6.2. Near Real-time Notifications

The Notifications dashboard presents three different levels of notifications to the user:

1. Alerts that require urgent attention of the user and require an immediate decision.
2. Alarms that require further analysis from the user taking into account the context, recent inspection or second opinion from experts, but no immediate intervention is expected.
3. Events that are reported as non-critical but in correlation with frequency and other information can be useful to contextualize situations.

The following picture is a screenshot of the notification's dashboard.


Figure 8-7: LOCATE App Notifications screen

## 8.6.3. Global Performance Status

The Global Performance Status intends to present concise information of the overall status of the locomotive. The dashboard presents a radar chart with the longest and shortest RUL predicted for each component. This illustrates variations between components and the components that are predicted to require a maintenance intervention in a shorter timeframe.

The following figure is an example of the Global Performance Status.

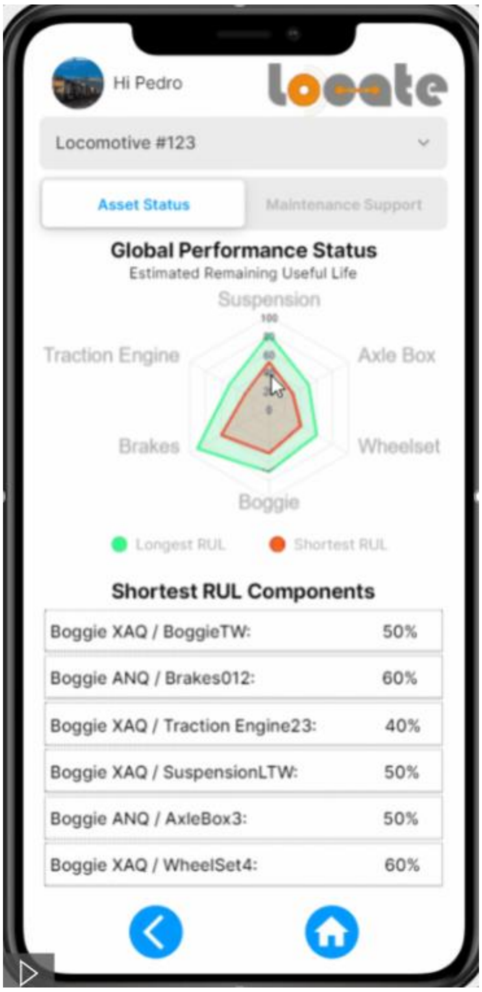



Figure 8-8: LOCATE App Global Performance Status screen

### 8.6.4. Remaining Useful Life Status

The predicted RUL Status is divided in two different dashboards, one that presents the components status, e.g. Power Spectral Density (PSD) or box plots charts, depending of the specific component analysis. The second is the predicted RUL degradation profile over the component usage.

The following figure shows an example of the RUL status dashboards.

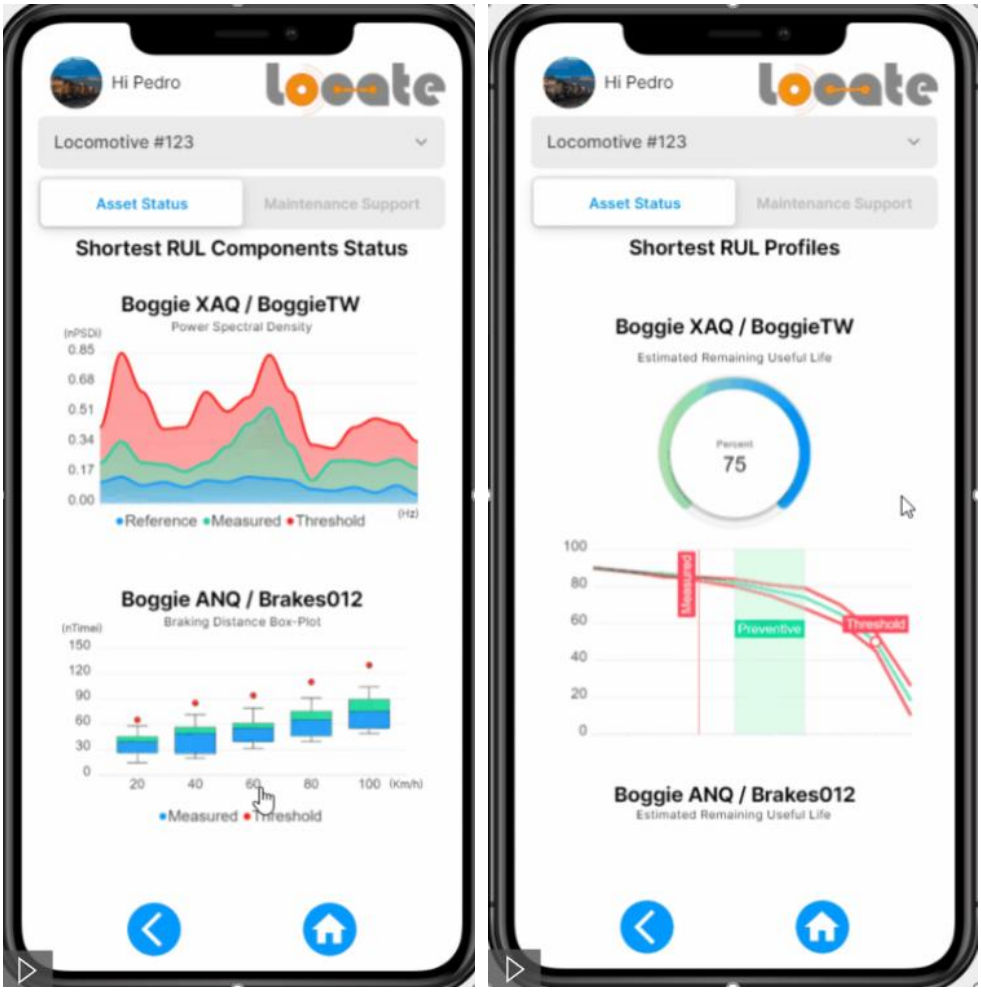



Figure 8-9: LOCATE App Shortest RUL status and profiles screens

### 8.6.5. Planned Work Orders

The following figure shows an example of the planned work orders screen that are retrieved from the 3rd party maintenance tool.

The work orders can be classified by different levels of severity, which are also presented on the screen as a red, amber, and green rating.

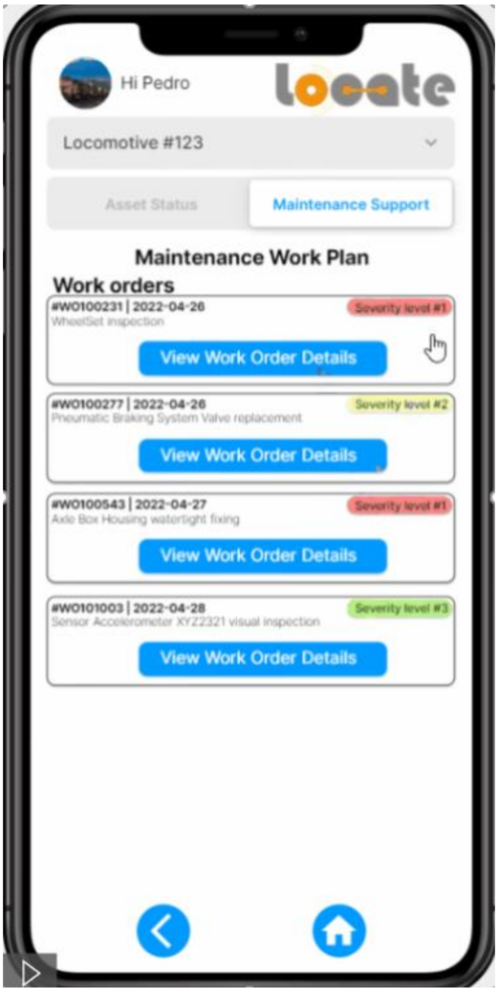



Figure 8-10: LOCATE App Maintenance Work Plan screen

### 8.6.6. Optimized Maintenance Scheduling

The LOCATE App provides a dashboard comparing the planned maintenance activities from a preventive maintenance approach with optimized scheduling taking into account the predictive maintenance and the estimated RUL figures for each component.

The following print screen depicts the Optimized Maintenance Scheduling screen.

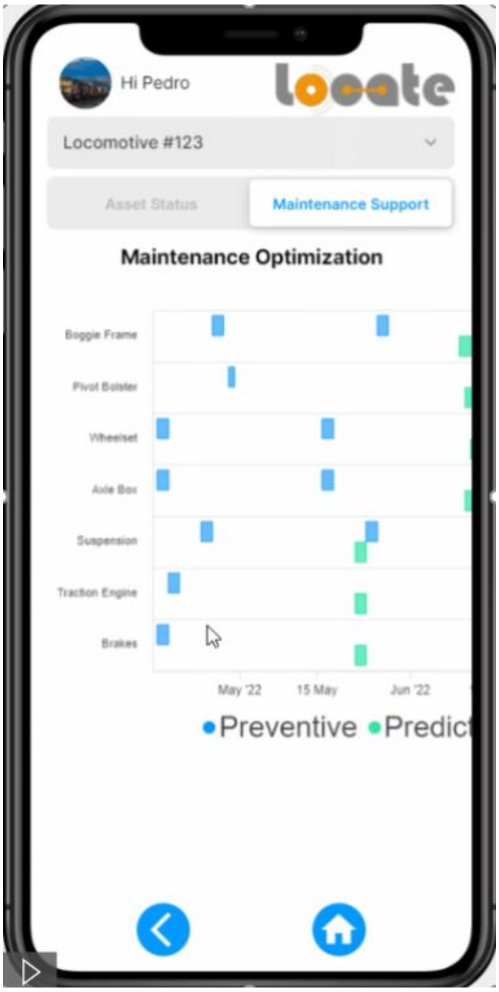



Figure 8-11: LOCATE App Optimized Maintenance Scheduling screen

## 8.7. LOCATE Framework Adequacy Evaluation

The demonstrator enabled the proof-of-concept and validation of the end-to-end framework designed in LOCATE. This chapter assesses the adequacy of the solution implemented into five dimensions divided by sensors set, data insights, SW features, Users Interface, and Installation aspects.

| Demonstrator Dimension | Solution Adequacy Analysis |
|---|---|
| Sensors set | The sensors set was initially identified at simulation level as part of the digital twin design, and later at demonstrator installation stage validated from location feasibility point of view. Later the data insights supported the sensors set and layout to be adequate and pairing well with the digital twin simulations. |
| Data Insights | The demonstrator proved to provide a good adherence between the reference library and measurements, including the post processing analysis. |
| SW features | The software features included the end-to-end framework needs in terms of the different pipeline stages, from the data collection, edge computing and cloud web-services, incorporating the interfaces to third-parties and interaction with the reference library and digital twins. |
| Users Interface | The software interface considered the different system users and followed a mobile-first approach focused on the user experience to stress the need for actionable and concise information. |
| Installation Aspects | The demonstrator was designed and executed to cope with the harsh environment and protected against external interferences and restrict the radiated and conducted emissions as well. |

Table 8-3 : 8.7. LOCATE Framework Adequacy Evaluation

## 8.8. Product Roadmap

The LOCATE project demonstrated the end-to-end framework of a CBM solution for bogie monitoring. There are few important steps that needs to be implemented and consolidated to be able to productize the LOCATE developments.

The product roadmap includes three vectors that needs to be consolidated:

- Technology solution consolidation and related engineering activities
    - Integrated/ embedded measurement systems could introduce significant improvements:
        - Power efficiency and autonomy
        - Miniaturization and less space dependent
    - Wireless sensors
        - Installations without wiring and cabling
        - Installation simplification and time efficient
    - Onboard machine learning and AI
        - Data reduction and communications efficiency
        - Intelligence flow-down and anomaly detection closer to the sensors
        - Simplified data pipeline architecture

- Data
  - Vehicle Response Library and Swarm/Fleet dataset intelligence
  - Incremental knowledge
  - Maintenance Operations Intelligence feedback
- Operations
  - Business driven culture with optimisation figures and KPIs
  - Condition Monitoring as part of the maintenance policy
  - IT/OT holistic operations, training, and support

The technology vector is probably the more straightforward, since the technology is available, it requires only engineering. The data vector needs to be seen as incremental and respective value added will improve and compound over time impacting the entry business. The operations are most likely where the product needs to be consolidated to overcome the business friction where the data storytelling is not sufficient to convince the added-value.

The product roadmap is defined, and plan settled. There are initiatives in place to progress with the roadmap execution.

# 9. Conclusion and Lessons

This chapter captures the main conclusions and lessons learnt from the demonstrator integration and validation.

The measurement campaign is globally a success.

All the sensors operates correctly: no disconnection, no loose of signal, no loose of measurement data. The data recorded are qualitative.

Maintenance team of FGC did not notice any inconvenience regarding the integration of the demonstrator.

It was a big challenge to develop a low power device in 2 months to overcome the power constraints coming late in the project.

There was 4G communication problem due to tunnel and over consumption of power in order to transfer all the raw data measured.

The work with FGC maintenance team allows to highlight 'standard' difficulties due to retrofitting a locomotive with sensors. Indeed, the integration of sensors for long term measurement campaign has a strong impact on maintenance operation. For example, an accelerometer on the axle box is not so easy to put without impacting maintenance operations: need no connector to be robust but need to be removed to make operation on axle or bearing). The integration is a long iterative process that took more time than initially estimated.

Another 'standard' difficulty is when working on old generation of material with operator, the operator does not have CAD or available drawings on some parts. Some drawings are manufacturer properties and then are not available. It necessitates to have an iterative process to define solutions, design parts, discover new problem to solve concerning integration, wire path, impact on maintenance operation or rolling stock integrity.

On the use of implemented sensors: some sensors are already existing and distributed on the locomotive but most of the time the operator cannot access easily to the information and the connexion to the existing sensors are banned in order to reduce possible disturbenes ont the locomotive. That is why there is no tachometer implemented.

There is no correlation map allowing to have the Kilometric Points location with GPS location. This is also an important problem to be able to record and/or analyse the measurement without KP point information.

Concerning the architecture: Locate project validates the requirements to have a flexible and adaptive system due to integration constraints induced by retrofitting an old system. It necessitates to have a flexible architecture with the possibility to condition different sensors, be able to be distributable and resist to harsh environment.

On software side, the flexibility is a key point because this monitoring device needs to be updated regularly in function of the steps of monitoring process :

1. Set up and validation of sensor installation
2. First measurements of complete track define the best suitable section and indicators and make correlation with reference model, develop digital twins

3. Optimization of indicators and threshold in function of maintenance feedback and monitoring data examination.(this is a continuous process).

Concerning the analysis of raw data and creation of measurement library :

Tools have to be develop in order to be able to make examination on each runs individually and on averaged situation with possibility to adapt indicators in function of operational behaviour.

This kind of tool is not easy to industrialize and standardize due to the complexity of the algorithms to develop and combination of signal and sensor data. Indeed, the acceleration level is 10kHz have to be normalized using an instantaneous speed recorded at 10Hz.

Finally, it is also observed that the maintenance teams are not ready to manage the amount of data generated by monitoring system distributed on all the rolling stock material.

Their interest for next 5 to 10 years are mainly to enhance their inspection using inspection tools and correlate their inspection with operational behaviour.

Finally priority should be to define an autonomous system for correlation between inspection values (like wheel profile measurement) and bogie stability detection or life time extension. The use of a correlated referenced model is a key point to converge quickly to a reduced data set in order to inspect the locomotive during its normal operation using a periodic inspection plan (a system each 6 months).

In what concerns the dependency to track sections of measurements, the use of PSD profile independently to section can be done to monitor the vibration level and detect abnormal situation in Z direction on bogie frame and axle box.

On Axle box, the load on the engine is important and can change significantly the vibration level. Triggering the acquisition to same load condition is as important as the knowledge of the speed of the locomotive.

On Y direction the PSD profile are mainly governed by phenomenon due to interaction between the locomotive and the track. The edition of a PSD profile independently of the section is not possible.

Regarding the reference model, the main conclusions can be highlighted:

- Duration of the time signals has an impact on the quality of the transmissibility based damage indicators;
- Small sensitivity of the TDI to 20% cross section crack. However, TDI is sensitive to moderate to large craks (63 to 100%);
- TDI effectively detects moderate to large spring stiffness reduction (-50%);
- TDI effectively detects moderate to large variation of the damping coefficient (+-50%);
- Maximum occurrences approach is globally sensitive to damage in bogie frame and allows damage location; the resuls are inconclusive regarding the failure of suspension elements;
- Surrogate models of the standard deviation of the lateral acceleration of the bogie frames show good fit, low absolute percentage error, and sensitivity to spring damage;

- Upper and lower stifness limites were defined for discrete speed intervals based on the variance of the surrogate. The maximum and minimum of the surrogate within the stifness limits constitute the threshold for the response.

The LOCATE project identified the framework with a reference library and digital twin and bi-directional feedback to and from maintenance executions. Those feedbacks will enable to calibrate and improve the thresholds and constraints definitions.

Due to the shorter timeframe of the demonstrator, and considering the fact that the demonstrator was installed immediately after a significant maintenance intervention on the locomotive bogie, it was not possible to observe degradations during the demonstrator. Despite the good adherence of the results with respect to the reference library, it doesn't enable the contribution to the failure rates and degradation models calibration, but the framework established the approach and can be adopted on a larger timeframe deployment and expand to locomotive fleets.

# 10. References


[1] Sampaio R.P.C., Maia N.M.M. Strategies for an Efficient Indicator of Structural Damage, Mechanical Systems and Signal Processing, special issue on "Inverse Problems". 2009;23,1855-1869

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[3] Heylen W, Lammens S, Sas P. Modal Analysis Theory and Testing. K.U. Leuven - PMA, Belgium; 1998. p. 340