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1. Executive Summary

This document, deliverable **D2.1 Architecture Input Requirements Consolidation first version** in FP3-IAM4RAIL, outlines a high-level system architecture aligned with EU RAIL Multi-Annual Work Programme (MAWP). The Scope of D2.1 is to define a first issue for the definition of FP3-IAM4RAIL project architecture, including a description of innovation and an introduction to the business assessment.

This first definition will cover how the proposed developments go beyond the state-of-the-art, including the current architecture of the systems, and a high-level architecture overview of the proposed demonstrators constituting building blocks which will be built up into a holistic approach in **D2.3 Architecture Requirements Consolidation final version**. Figure 1 shows the project outline scope:

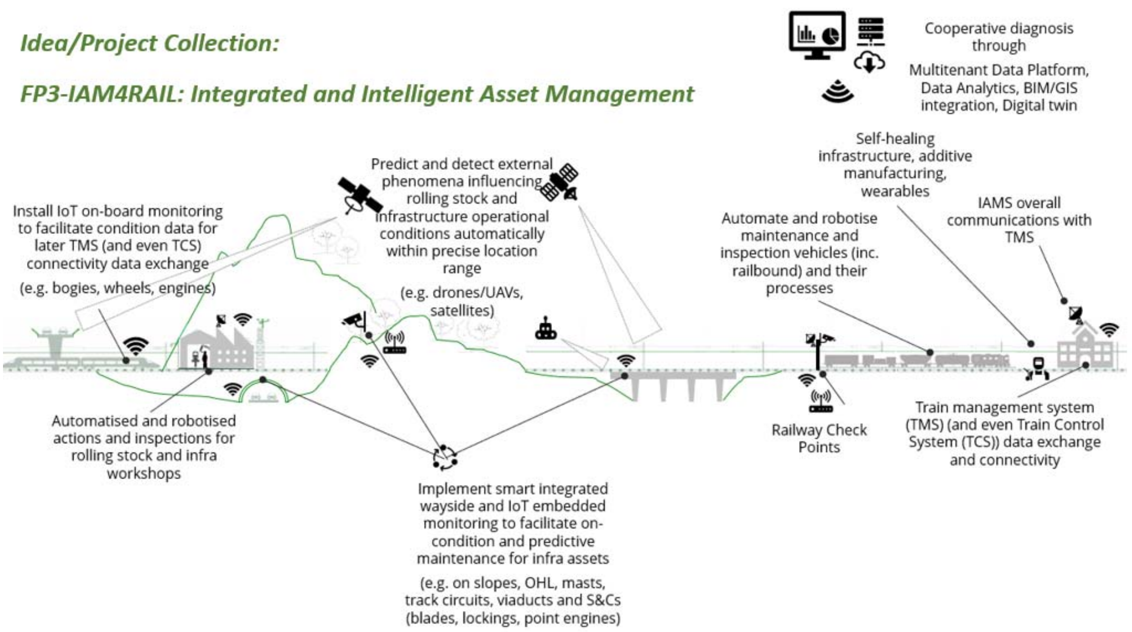

Figure 1. Outline overview of IAM4RAIL project.

The architecture definition incorporates a chapter per cluster in which in which the specific data needed as input and the expected output is explained. In addition, the current architecture, followed by the dataflow and the expected developments to be achieved in the demonstrators, is explained at a high-level. A comparison between the current and new systems (which include ML, IoT, Data Analytics, AI…) is also provided.
Finally, different examples about some expected sequenced diagrams are provided to give a better understanding of the data flow.

In a second step, **D2.3 will be published at a later stage**, and will summarise in more detail, considering the architectural requirements, the lessons learned and the holistic approach concept. It will also identify the way forward toward the future TRL 8/9 implementation of Intelligent Asset Management Systems (IAMS) within the organisations involved, trying to draw general conclusions from the experience of the Use Cases (UC), the demonstrators and the different results.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
ABA	Axle Box Acceleration
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Model
CBM	Condition Based Maintenance
CCS	Control Command and Signalling
CCTV	Closed Circuit Television
CM	Corrective Maintenance
CNN	Convolutional Neural Network
DSS	Decision Support System
DT	Digital Twin
ECN	Ethernet Consist Network
ED	End Devices
ENE	Energy
ERJU	Europe’s Rail Joint Undertaking
ETB	Ethernet Train Backbone
FEM	Finite Elements Modelling
FRMCS	Future Railway Mobile Communication System
FP	Flagship Project
GA	Grant Agreement
GPR	Ground Penetrating Radar
GSM-R	Global System for Mobile Communications – Railway
HABD	Hot Axle Box Detector
HMI	Human-Machine Interface
HTTPS	Hypertext Transfer Protocol Secure
HVAC	Heating, Ventilation and Air Conditioning
IAMS	Intelligent Asset Management Systems
IM	Infrastructure Manager
INF	Infrastructure
IoT	Internet of Things
IXL	Interlocking
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCC	Life Cycle Costing
LiDAR	Light Detection and Ranging
MAWP	Multi Annual Work Programme
MBM	Multi Body Modelling
ML	Machine Learning
NG-TCN	New Generation Train Communication Network
OMTS	On-board Multimedia and Telematics
PM	Preventive Maintenance
RAMS	Reliability, Availability, Maintainability and Safety
RFID	Radio Frequency Identification

Abbreviation / Acronym	**Description**
RST	Rolling Stock
RU	Railway Undertaking
S&C	Switches & Crossings
TC	Track Circuits
TCN	Train Communication Networks
TCMS	Train Control Monitoring System
TMS	Train Management System
TRL	Technology Readiness Level
UC	Use Case
VC	Virtual Coupling
VPN	Virtual Private Network
WAP	Wireless Access Point
WED	Wireless End Devices
WP	Work Package
XML	Extensible Markup Language

Table 1: List of abbreviations and acronyms.

3. Background

The present document constitutes the **D2.1 Architecture Input Requirements Consolidation first version** in the framework of the Flagship Project FP3–IAM4RAIL, as described in the EU-RAIL MAWP, and contributes both to the Flagship Project FP1–MOTIONAL with **D26.1 Process to collection of use cases and establishing cooperation with all Destinations and System Pillar** & **D28.1 Summary on other Destinations Digital Twin use cases**, and the Flagship Project FP5–T RANS4M-R with **D25.3 Report on the basic functional and technical specifications regarding CMS as relevant input for FP3–IAM4RAIL.**

One of the main aims of the project is to facilitate the adoption of predictive maintenance supported by Condition Based Maintenance (CBM) as the core of asset management for railway assets, minimising the needs of corrective and preventive maintenance. Thus, that would suppose the corresponding cost saving during the entire lifecycle of the assets.

Overall, the FP3-IAM4RAIL Flagship Project aims to provide innovative technical requirements, methods, solutions, and services - including technical requirements and standards for future developments - based on the latest cutting-edge technologies, to minimise asset lifecycle costs and extend service life while meeting safety requirements and improving the reliability, availability and capacity of the railroad system. Both infrastructure and rolling stock are addressed.

The FP3-IAM4RAIL Flagship Project will research, develop and deliver solutions that will be demonstrated in different relevant scenarios across Europe, targeting up to TRL 6 as European common integrated solutions. Due consideration will be given to certification and validation of the new technologies and processes as part of those demonstrators, grouped in clusters, depending on the involved elements, and supported by a set of different Use Cases, integrating different technical enablers.

FP3-IAM4RAIL has defined 6 different clusters that include the most critical elements to be optimised:

- **Cluster A - Transversal Activities**: this cluster unifies the common activities of the project including project coordination (WP1); system vision, architecture and validation (WP2); and dissemination, communication and exploitation activities (WP20).
- **Cluster B - Wayside Monitoring and Traffic Management System Link**: this cluster focuses on the design, development, testing and validation of an Intelligent Asset Monitoring System capable of supporting the railway operators and infrastructure managers in maintaining smooth and uninterrupted operations (WP3 and WP4).
- **Cluster C - Rolling Stock Asset Management**: On-board and Wayside

Technologies. This cluster addresses both on-board (WP5 and WP6) and wayside (WP7) monitoring technologies for the design, testing and validation of intelligent rolling stock asset management solutions.

- **Cluster D - Infrastructure Asset Management:** the infrastructure asset management cluster addresses long term maintenance and costs (WP8), track systems (WP9), innovative multi-purpose IAMS infrastructure applications (WP10 and WP11) and civil assets including structures, earthworks and geotechnics (WP12 and WP13).
- **Cluster E - Railway Digital Twins**: this group of developments focuses on the implementation of railway Digital Twins across the rail sector (WP14 and WP15).
- **Cluster F - Environment, User and Worker Friendly Railway Assets:** this cluster has the objective of creating environment, user and worker friendly railway assets addressing environmental and cost-effective lines (WP16), new additive manufacturing repair processes (WP17), robotic platforms for railway interventions (WP18) and Augmented Reality and exoskeletons to support railway maintenance (WP19).

4. Objective/Aim

The main scope of this document is to provide a general overview about what requirements are necessary to accomplish with the needs for a successfully deployment of the different demonstrators and, thereby, to define how the architecture and the data exchange of the involved systems and sub-systems are.

To achieve the objective, the systems will be deployed in environments with different characteristics (Netherlands, Norway, Spain) which will allow to analyse and use different data to cover every aspect during railway operation. Although each cluster has its own scope and involves different data sources and results, all of them follow the same methodology. A detailed analysis is performed below with the aim to have a general overview of the needs for each demonstrator.

Within FP3-IAM4RAIL, a total of seven integrated demonstrators have been defined to bring together the individual developments in the various work packages to a coherent and holistic approach.
Figure 2 summarises this approach. Extracted from it, we could focus on Infrastructure Assets.

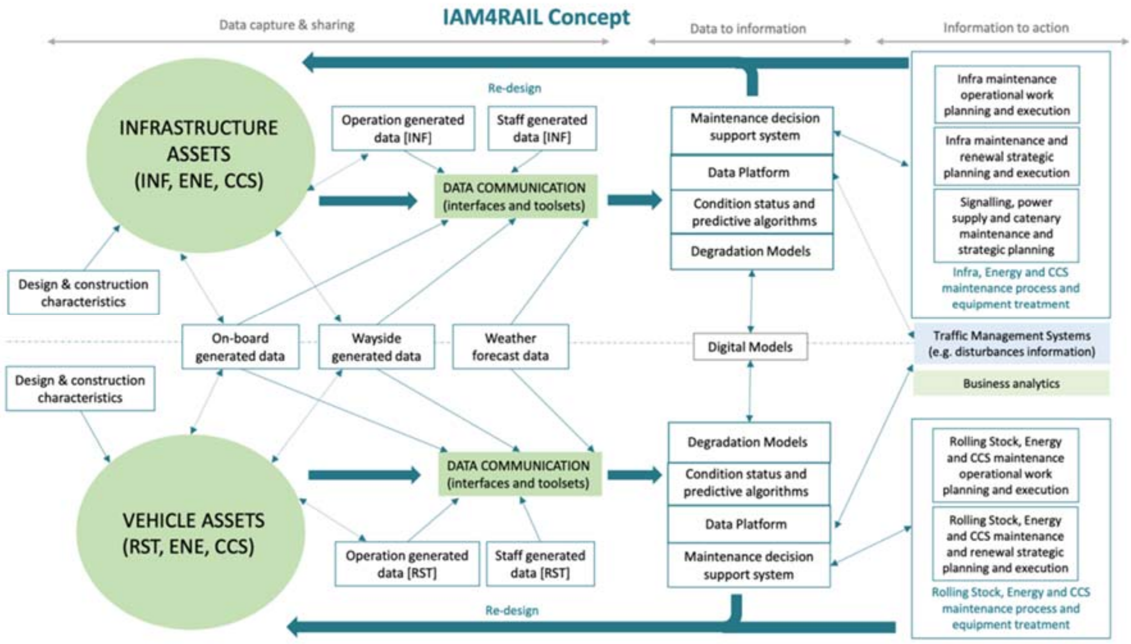

Figure 2. FP3-IA4RAIL Concept.

- INFRASTRUCTURE ASSETS (INF, ENE, CCS): focus will be in infrastructure assets, particularly for assets along the railway line within a range of 360 degrees and approximately 5 meters around each asset. Main examples of potential target assets are switches & crossings, track, catenary, signals, etc.

- Design & construction characteristics: design and construction characteristics of assets are necessary to parametrise algorithms and models. These characteristics include materials, geometries, installation & assembly, etc. The focus will not only be in characterising infrastructure assets: the design & construction characteristics of vehicles operating along the pilot lines are necessary too, as assessing their interaction with the infrastructure (e.g. wheel-rail interaction) is key to evaluate their impact in the degradation of infrastructure assets.

- On-board generated data: data generated by sensors and systems installed on-board Leonardo platform (see section 6.1), either raw or processed. Some examples of this data are 2D images, 3D point-clouds (LiDar, laser-scanner), inertial (accelerations & gyros, displacements, etc.), GPR, etc.

- Wayside generated data: data generated by sensors and systems installed in the track and in the vicinity of switches and crossings, either raw or processed. Some examples of this data are inertial (accelerations, displacements, forces, etc.), electrical (e.g. currents and voltages), temperature, acoustic emission, etc.

- Operation generated data (INF): data generated during operations may include information about the status of assets (e.g. track geometry inspection data), services operating along the line (including the characteristics of vehicles, speeds, loads, etc.).

- Staff generated data (INF): data generated by maintenance staff may include information about the status of assets (e.g. visual/manual inspections), history of reparations and replacements, maintenance plans, etc.

- Data Communication (interfaces and toolsets): sensors and systems (both on-board and wayside) will include some means to transmit relevant information to back-office applications. Focus will be in the interoperability of systems; for that reason, a common data model approach will be followed for the different interfaces.

- Maintenance decision support system: set of tools and functionalities that will assist decision-makers in making informed choices for maintenance work planning and execution based on the analytics and insights generated by the system. Example of these functionalities include the detection of anomalies and the diagnostic of failures, as well as the comparison and benchmarking of health condition data and its projected evolution.
  These tools and functionalities include the integration and visualization of data (including multiple type and historical information data analysis) in IAMS.

- Data platform: Implementation of the Rail Data Space to provide exchange and sharing of digital resources across rail operators, infrastructure managers, suppliers and service providers involved in the maintenance activities and processes. The data platform is based on data federation services for building a trusted, reliable, cybersecure federated data space connecting all stake holders.

- Condition status and predictive algorithms: the health condition of target assets will be assessed by means of different data sources, models, and algorithms. Based on that, the future condition status will be assessed by means of predictive algorithms that will be based on physical degradation modelling, machine learning techniques, and a combination of both (hybrid modelling).

- Degradation models: development of digital models (see below) will allow assessing the degradation of infrastructure assets, taking into account the interaction between assets and the characteristics of their lifecycle. Degradation models can be theoretical and/or based on the experience (analytical approach), but they can also make use of historical data to enable approaches based on machine learning. Both approaches will be used for the development of predictive algorithms (see above).

- Digital models: models of assets (of both vehicles and infrastructure) are key to the development of condition status and predictive algorithms, as well as for assessing their degradation (see above). We will make use of different kind of modelling techniques: analytical, Finite Element Modelling (FEM), Multi Body Modelling (MBM), data-based (e.g. using machine learning techniques), etc.

- Infrastructure maintenance operational work planning and execution: The information provided by condition status and predictive algorithms and maintenance decision support system will enable a more effective planning of maintenance operational work in the short term. The goal is to transform the information into action (execution) by prioritising cost, safety, and availability.

- Infrastructure maintenance and renewal strategic planning execution: all the above will be fed back into the system to support better strategic decisions in the mid-long term.

As a result of the large number of elements involved in FP3-IAM4RAIL program, it is mandatory to differentiate the systems with an important role in railway management. The clusters have been defined according to the actors and the services affected, as well as the connections between them. As explained in chapter 3, due to the great variety of demonstrators and the characteristics to be considered, they will be deployed in different environments.

Two different approaches can be highlighted to achieve the objectives:

- Utilisation of new technology and its data: this includes not only the use of current technology and data, but also the analysis of new technology systems and the data provided by them. Data collection and integration, as well as how it affects maintenance activities, is one of the main scopes of the project. It involves deploying the sensors on the rail infrastructure subsystems, including wayside and onboard sensors, to gather sensor data relevant to extract diagnostic and prognostic information.
  Using these sensors, the project aims to provide traceable data for continuous monitoring of asset condition, which will allow maintenance experts and asset managers to make informed decisions, thus enabling them to identify specific asset problems, possibly at an early stage, and to predict their evolution in order to plan appropriate interventions.

- Utilisation of machine learning and artificial intelligence: by using data analytics, different models based on ML and AI will be developed and evaluated with the aim of providing new solutions to optimise maintenance activities. These models will consider not only current data but also data provided by new technologies. By combining data findings and the use of advanced algorithms, the aim is to create effective solutions for maintenance decision-making. By embracing data integration and modern analytics, the industry can significantly improve fault detection capabilities, resulting in better maintenance practices, improved resource allocation and safer and more reliable railway operations.

The following table summarises the Use Cases to be deployed and the clusters these Use Cases belong to:

Cluster B: Wayside Monitoring IAMS and TMS link
UC 3.1 - Wayside and Infrastructure IAMS for TMS optimisation
UC 3.2 - Wayside monitoring in conventional and high-speed lines for TMS optimization
Cluster C: Rolling Stock Asset Management
UC 5.1 - Bogie Monitoring System (on-board)
UC 5.2 - Health Monitoring & Analytics of HVAC & Brake systems (ES)
UC 5.3 - Health Monitoring & Analytics and ML algorithms development of HVAC, Doors, Batteries, Brakes, Sanitary Systems, Traction & Auxiliary systems (NL)
UC 5.4 - Health Monitoring & Analytics and ML algorithms development of Traction, HVAC, Doors, Batteries, Brakes, Traction & Auxiliary systems (ES)
UC 6.1 - Development of next generation Traction Control unit hardware and gate drive communication link
UC 6.2 - Traction Component Health Monitoring & predictive Maintenance
UC 6.3 - Set up of adaptative wireless telecom network between train elements
UC 6.4 - Adhesion estimation for management
UC 6.5 - Wayside signalling equipment monitoring system
UC 6.6 - On-board bogie diagnostic solution for fault detection applied to train(s) operating in Germany
UC 6.7 - Digital twin for energy
UC 6.8 - Smart maintenance scheduling tool
UC 7.1 - Bogie Monitoring System (wayside – acoustic, 2D-3D images, video and laser)
UC 7.2 - Pantograph Monitoring System (wayside – video and 2D-3D images)
UC 7.3 - General physical anomaly detection Monitoring System (wayside – video and 3D images)
UC 7.4 - Railway checkpoint use case (ES)
UC 7.5 - Railway checkpoint use case (NL)
UC 7.6 - Data path diagram Use Case
UC 7.7 - Data Analytics for Railway Checkpoints Use Case
UC 7.8 - Optimization of rolling stock maintenance Use Case
UC 7.9 - CBM algorithms for freight
Cluster D: Infrastructure Asset Management
UC 8.1 - Long term asset management and LCC
UC 8.2 - Holistic long term asset management
UC 9.1 - Sensing railway superstructure system components
UC 9.2 - Railway infrastructure monitoring using optic fiber
UC 9.3 - Track Geometry and S&C condition monitoring
UC 9.4 - Infrastructure monitoring solutions
UC 9.5 - Prescriptive maintenance solutions
UC 10.1 - Linking (new) monitoring technologies to asset management issues

UC 10.2 - Fusion of (onboard and wayside) monitoring data for an enhanced fault detection and diagnosis
UC 12.1 - Multiscale monitoring of civil assets
UC 12.2 - Bridges and earthworks assets management aided by geotechnics
UC 12.3 - Monitoring of tunnel, sub-ballast layers, subsoil and predictive maintenance for tunnels
UC 12.4 - Data Analysis for condition monitoring
Cluster E: Railway Digital Twins
UC 15.1 - Decision support systems for railway station asset management
UC 15.2 - Virtual Certification Framework
UC 15.3 - Demonstration of automatic track visual inspection by unmanned means (drones)
UC 15.4 - BIM model as support to communicate and populate the Station's Asset Management System
Cluster F: Environment, User and Worker Friendly Railway Assets
UC 16.1 - Green tracks and turnouts
UC 16.2 - Resilient lines and sustainable lines
UC 17.1 - In-situ AM repair machine for rails, switches and crossings
UC 17.2 - AM repair machine for wheels
UC 17.3 - In situ repair of track metallic assets
UC 17.4 - Stationary solution for AM repaired turnout crossings using WAAM technology
UC 17.5 - Additive Manufacturing of large & flame-retardant polymer spare part
UC 17.6 - Digital warehouse
UC 18.1 - Light and flexible on-track inspection
UC 18.2 - Automated installation of ERTMS balises and axle counters
UC 18.3 - Disinfection of trains and small stations
UC 18.4 - Train underbody inspection
UC 18.5 - Automated crossing repair
UC 19.1 - Upper-body exoskeleton for worker's support in railway industry
UC 19.2 - Augmented Reality tools to help and guide railway workers in maintenance operations

Table 2. Summary of demonstrators

5. General High-level architecture description

FP3-IAM4RAIL plays a significant role in fostering enhanced integration and collaboration among various stakeholders, both within and outside the rail ecosystem.
Consequently, FP3-IAM4RAIL's underlying concept outlines its dynamic approach to interlinking different components: the railway infrastructure (INF), the energy subsystem (ENE), the control command and signalling subsystem (CCS) and the rolling stock (RST). This is accomplished through a phased process comprising three main steps:

- Data Capturing & Sharing: this phase involves the acquisition and sharing of new data, facilitated by innovative means like wayside and on-board systems, as well as external sources.

- Transferring Data into Information: innovative digital models are employed to convert the collected data into actionable information and valuable insights, thereby transforming raw data into knowledge.
- Setting Information into Actions: the actionable insights derived from the previous step guide decisions and actions, driving improvements in various aspects of the rail ecosystem.

Figure 3 shows a schematic representation of the architecture to be followed by the systems.

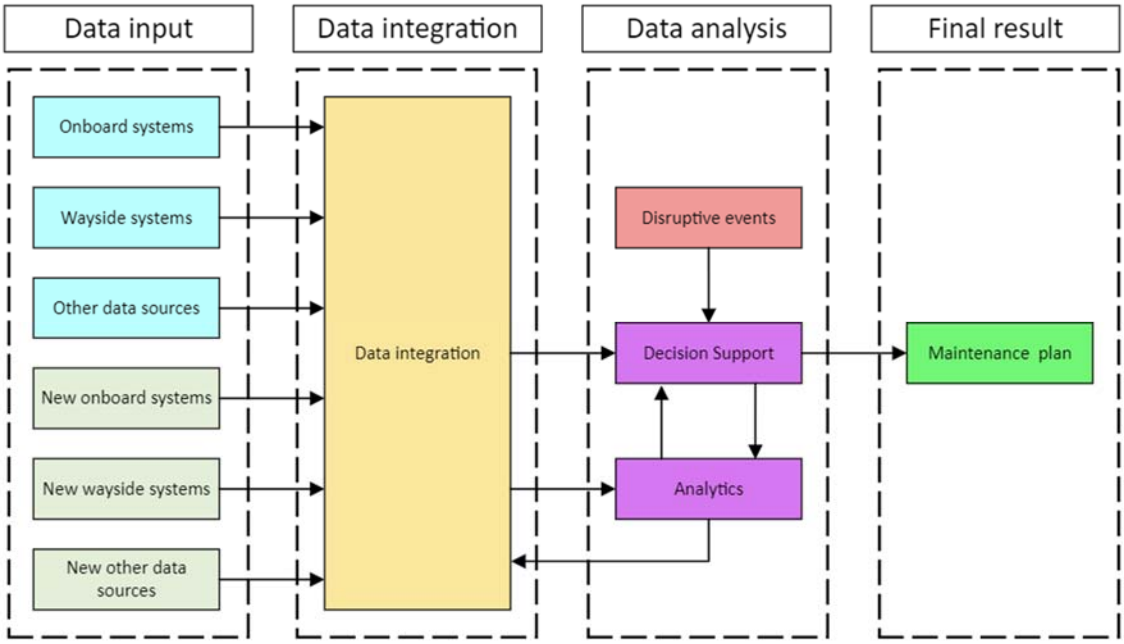

Figure 3. High-level architecture diagram.

- Data input: it involves the systems and components that provides data, in the current situation or with new technology. Generally, this data is provided for each system in its own format, so that a phase of processing data after its reception is needed. These systems can be classified into:
  - **Onboard systems**: it refers to the systems and components installed in the vehicles or equipment directly. These could include sensors, communication devices and other relevant technologies.
  - **Wayside systems**: it refers to the systems and infrastructure located along the track or wayside. These could include signals, switches, trackside sensors and other equipment used to monitor and control the railway.
  - **Other data sources**: it encompasses additional sources of data that contribute to the overall system. These sources might include external databases, such as weather information or third-party systems.

- Data integration: it encompasses the process of collecting, aggregating and harmonising data both from existing sources and new technological sensors, with the aim to create a unified and coherent dataset for analysis and decision making. This module includes the following phases:

  - **Collect data**: available data from the systems depend on the system which provides them. Quantity, quality, periodicity, importance, etc. are some of the parameters to consider as they change from one system to another and therefore needing to be standardised.
    In addition, it is possible that some systems can provide historic data from previously maintenance activities while others, which are based on new technology, need to be investigated to see if these new systems are valuable for optimising maintenance activities.
  - **Data preparation**: this is one of the most important phases during data integration, as it will provide the real input. Depending on the receiver, different treatment need to be accomplished.
    - **Data for end users**: this data needs to be prepared so that the decision support system can accept it. It involves data that is currently in the systems.
    - **Data for ML and AI models**: these data need to be adapted depending on its importance in maintenance activities and the model selected. It is important to have as much data as possible, as the model will need to be trained.

- Disruptive events: it includes every aspect during operation (in real time) that can affect the maintenance scheduled plan. Disruptive events include from a fault at signalling to a replanning in the target plan due to delays during operation.

- Analytics: it involves the application of data analysis techniques to extract insights, patterns and trends from the integrated dataset. It includes not only historic data based on the input elements from the integration module, but also the ML and AI models. Main Machine Learning algorithms are:

  - **Regression**: it is a predictive modelling technique (linear, logistic, polynomial…) that analyses the relation between the target or dependent variable and independent variable in a dataset.
  - **Decision tree**: it is a non-parametric supervised learning method used for classification which aims to create a model that predicts the value of a target variable by learning simple decision rules inferred from the data features.
  - **Random forest**: it is the combination of the output of multiple decision

trees.

  - **Neural networks**: it is a specialised type of deep learning algorithm mainly designed for tasks that need object recognition.

- Decision Support: it is the system that provides the tools and functionalities that assist decision-makers in making informed choices based on the analytics, disruptive events during operation and insights generated by the system to generate the maintenance scheduled plan. With the inclusion of new technology and the analytics module, it is expected to obtain an improved maintenance plan.

- Maintenance Plan: it is the final result of the process, where the maintenance activities are defined. It is important to highlight that the maintenance plan can change during operation due to disruptive events.

6. Cluster B: Wayside Monitoring IAMS and TMS link

6.1. Overview

Intelligent Asset Management Systems (IAMS) and Traffic Management System (TMS) link aim to meet the requirements for improving the connection and operation between the wayside signalling elements and the TMS. Cluster B focuses on the design, development, testing and validation of an Intelligent Asset Monitoring System, capable of supporting the railway operators and infrastructure managers in maintaining smooth and uninterrupted operations.

The activities performed in Cluster B are covered in WP3 and WP4, and the main scope is to improve the maintenance schedule plan by evolving from preventive + corrective maintenance to predictive (+corrective) maintenance.

To achieve this objective, different models based on AI, ML and IoT will be developed to measure where and when maintenance is needed, allowing the IMs and operators to improve their scheduled plan and, thereby, reducing costs.

Timetable optimisation, conflicts detection and resolution or capacity increased are the next step and they are out of the scope of this document, as they are the core of the activities performed in FP1-MOTIONAL WPs 4, 5 and 11, 12.

The following Use Cases have been defined to meet the requirements to perform the demonstrators:

- UC 3.1: Wayside and Infrastructure IAMS for TMS optimisation
- UC 3.2: Wayside monitoring in conventional and high-speed lines for TMS optimization

A detailed description about Cluster B and its objectives, current status and KPIs can be found at **D2.6 Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue).** In addition, specific information about data exchange, including the type of data and its format will be defined at **D2.2 Definition of inputs for TMS specific Data Structure and D3.1 IAMS Vision, Validation & Architecture Report**.

6.2. Involved elements

In order to provide with a general overview of the current situation and the involved systems, the following elements can be found:

- Traffic Management System: TMS is the main element for a successfully railway management. It is the system in charge of managing the scheduled, targeted and forecasted activities on the track, not only for train movements, but also for maintenance activities.
  It is the nerve centre from where each order is determined and it is followed by other systems and involved actors. TMS uses the information on the systems collected by the diagnostic functions to provide operational support for the management of maintenance interventions. In addition, TMS includes the following sub-systems:

  - **Asset Status Forecasting System**: based on the information and the data collected by the following sub-systems, several specific Machine Learning models will be developed and applied in order to solve the most critical issues that affect the operation related to level crossing and signalling equipment.
  - **Decision Support System for Automatic and Optimised Maintenance Scheduling**: the DSS is aimed at suggesting possible alternative solutions in case of an interruption of the line due to planned maintenance interventions and shall consider the costs for the service manager and the users involved in the service interruption.
  - **Integration of Analytics with TMS**: information on the diagnostic status of the signalling devices, track and infrastructure can be fed back into the TMS in order to improve and optimise the scheduling on the line.

- Wayside Signalling Equipment Monitoring System: it focuses on the remote and non-intrusive collection of diagnostic and operational data coming from the wayside signalling assets monitored.

  - **Point machines monitoring system**: current system is based on unmanned and no-supervised asset diagnostic and self-diagnostics for condition monitoring of wayside solutions. The most common failures in high-speed lines are the break of the lock bars of the point machines due to the vibrations and its own movements; and the slack in the “locks” to closure.

  - **Track circuits:** a track circuit is an electrical device used in railway systems to determine the absence or occupancy of a train on rail tracks. Electrical equipment continuously monitors this circuit to detect the absence of trains, and false occupancy readings must be minimised to avoid disruptions in railway operations.
  - **Axle counters:** an axle counter is a system used in railway signalling to detect the clear or occupied status of a section of track between two points. It provides the same information as the track circuit in a mechanical form. The system compares the count at the start with the count at the end. If they match, the section is presumed to be clear.
  - **Light signals:** signals provide the status of the track to the TMS and railway operators.

- Infrastructure Monitoring System: it provides real time information related to the geometry of the track, and structural health conditions of the bridges, obtaining a better holistic view of the network status.

- Level Crossing Monitoring System - Radar and Lidar Obstacle Detection System: it is a system whose main function is to provide information about the status of the level crossing. It is currently based on Radar and Lidar obstacle detection system and provides information related to vehicles unduly occupying the level crossing passage or sized objects falling from them between the barriers. This information is provided to TMS, where it is analysed by the operators and used to modify the daily plan or perform a new scheduled plan. The development and test of a level crossing obstacle detector, banking simultaneously on Lidar and Radar sensors, is within the scope of this project.

- Post-analysis system: post-analysis system is a repository of the TMS in charge of collecting the information provided by previous systems to analyse all this data set and understand past decisions. This system will be connected not only to TMS, but also to the analytics module, providing the required data to train the algorithm for predictive maintenance.

- Predictive maintenance module: it is a new system that will collect all the data provided as input by the previous systems and will provide suggestions on maintenance activities at the level crossing barriers. This system includes the Machine Learning process providing as output modifications concerning the maintenance plan.

- HTPPS connection: connection between the different modules is performed through HTTPS, a secure communication protocol, ensuring safety and security.

In addition, the following actors can be found:

- Infrastructure Manager: IM is the main actor involved in railway operations and it is the person responsible for modifying the timetable, solving conflicts due to delays, etc. Focusing on the demonstrator, IM has the role of providing data and has the rights for selecting the best option for the maintenance activities schedule.

- Maintenance Operator: maintenance staff are personnel dedicated to ensuring the proper functioning and upkeep of the rail infrastructure. They perform routine inspections, repairs and preventive maintenance on tracks, signalling systems, stations, rolling stock and other rail components. Their role is vital in maintaining safety, reliability and the overall operational quality of the rail network.

Based on the elements explained above, figure 4 shows, at a high-level, the current architecture of the systems.

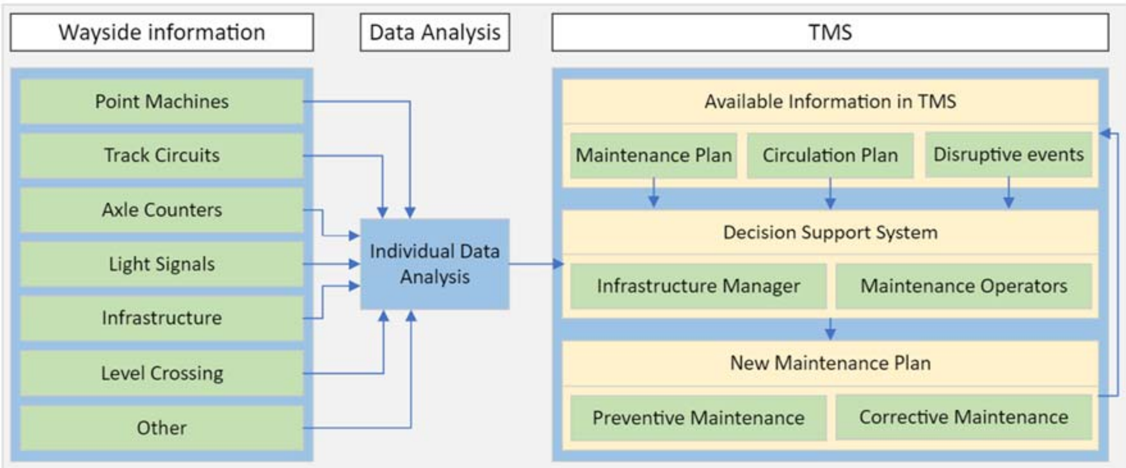

Figure 4. High-level current system architecture for TMS.

6.3. Methodology

The methodology to be followed focuses on implementing existing Wayside information and new technologies for increasing data availability from tracks rather than rolling stock information.

In addition, the main objective is the use of Machine Learning and Artificial Intelligent to obtain a better knowledge about the status of the Wayside information and, thereby, optimise the maintenance plan with the final aim to evolve from preventive + corrective maintenance to predictive (+corrective) maintenance.

It needs to be noted that corrective maintenance cannot be avoided, as it is a permanent problem to deal with. Therefore, by implementing Machine Learning methodology it is expected to reduce the impact and number of faults during operation, optimising the maintenance and the circulation plan.

Figure 5 shows the preliminary architecture of the involved elements.

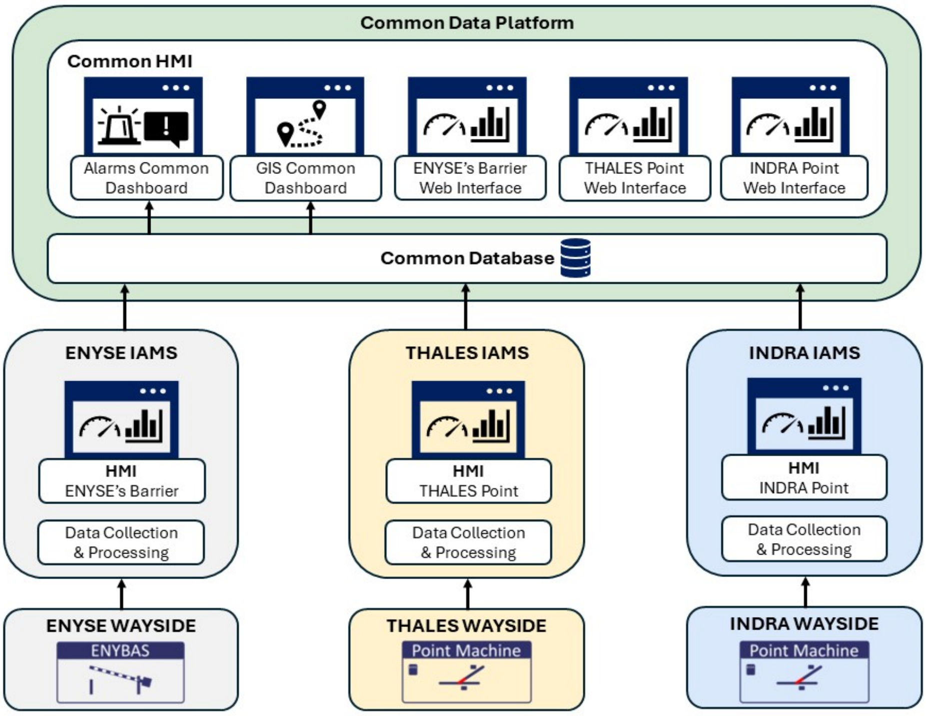

Figure 5. Preliminary architecture for IAMS.

In order to achieve the objective, the following steps should be taken into account:

6.3.1. Data collection

It is the starting point to perform a successful predictive maintenance plan based on Machine Learning methodology. This cluster focuses on improving the maintenance plan by optimising when and where it is necessary to perform a maintenance activity. For this reason, data collection represents a fundamental role to success. As it has been explained in chapter 5, there are two factors to consider:

- Quantity of data: the more available data, the better the result will be. In the cluster, quantity of data is improved by two methods:
  - Incorporating new technology;
  - Analysing existing datasets from previous maintenance activities.

- Quality of data: it is the second variable to consider. Quality data is as important as quantity, and the better the quality is, the better the results obtained will be.

By analysing previous datasets it is possible to determine which variables and format are needed to obtain valuable results.

6.3.2. Data Analysis

Once data to be used is selected, the following step consists of data preparation and the analysis of the different Machine Learning techniques. The availability of data and the type of variables are the main characteristics that will determine the model to use. As an example, for best results it is strongly recommended to use convolutional neural networks (CNN) with images as input.

Continuing with this example, even if enough images are available, all of them must have some previously processed parameters to be useful for the model (width, length, depth, size, pool layer...) and the processing order must not be decisive.

In addition, it is necessary to perform an analysis of the different results obtained, so that the best option according to the correspondent needs can be selected.

Figure 6 shows an example of a convolutional neural network operation.

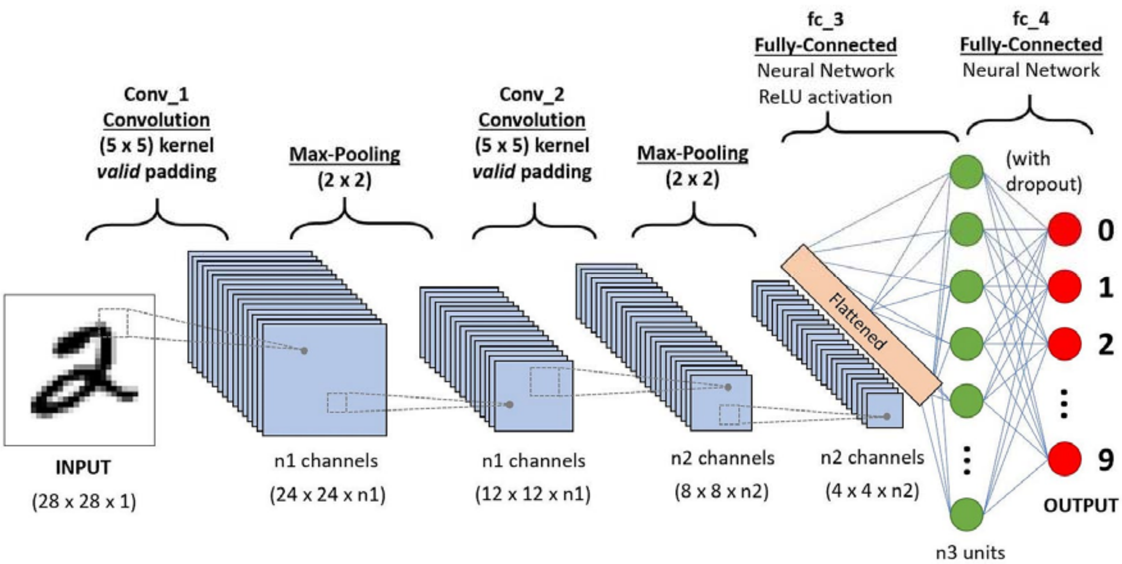

Figure 6. Example of convolutional neural network operation

6.3.3. New maintenance plan implementation

As a result of the implementation of data analytics explained in chapter 6.3.2, new input to perform the new maintenance plan is available. In this phase, Infrastructure Manager and Operation Managers discuss the best maintenance plan to perform for planning. On the other hand, the resulting maintenance plan is not decisive.

New input coming from disruptive events that can affect maintenance activities (delays on trains, lamp failure, catenary faults…) need to be considered to update and optimise the maintenance plan. For this reason, a feedback process between the maintenance plan, the disturbance events and the analysis module during operation is necessary to have up-to-date information related to each event occurring in real time.

Figure 7 shows a detailed outline of the proposed architecture.

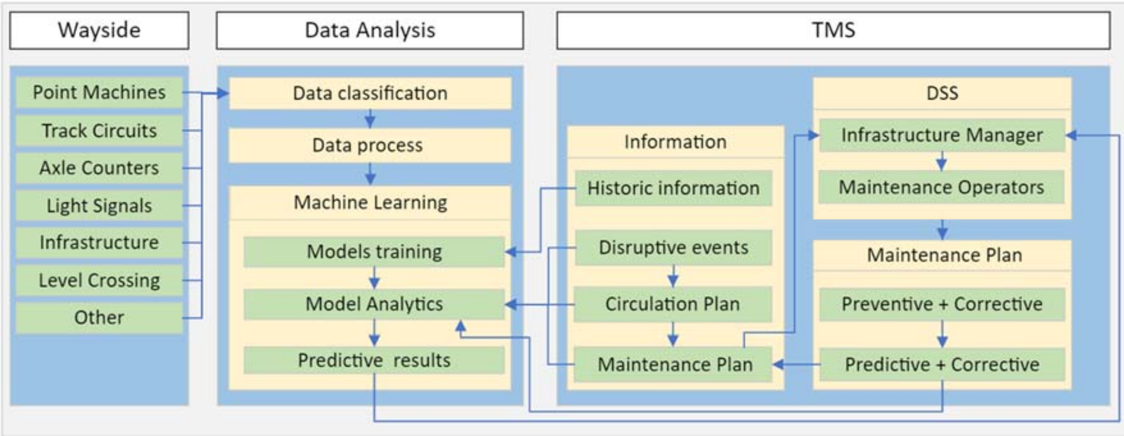

Figure 7. Architecture with Machine Learning module.

6.3.4. *Final result*

As a result of the analysis performed during the previous sections, it can be concluded that Cluster B focuses on improving maintenance activities not only by increasing the amount of available data by using new technology (IoT), but also with the analysis of the current available data and the use of Machine Learning models.

The implementation of these techniques and how they affect during operations will be a fundamental input to perform an optimised predictive maintenance plan and, therefore, an improved circulation plan.

The following figure shows an example of a sequential diagram between the schemes explained in the previous sections and what the data flow looks like in real-time operation:

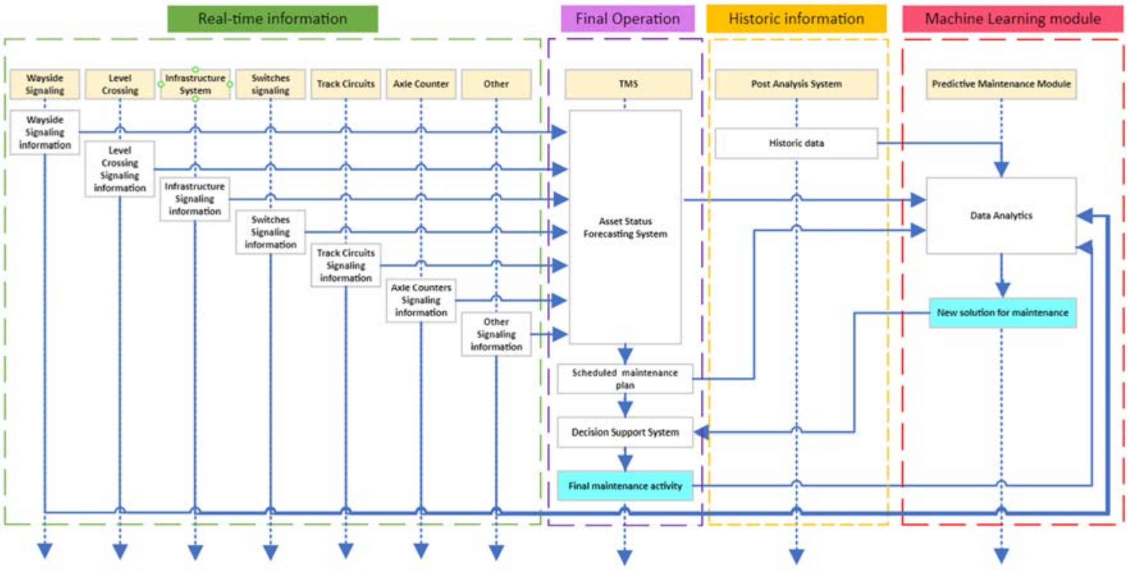

Figure 8. Sequence diagram for Wayside Monitoring IAMS and TMS Link.

7. Cluster C: Rolling Stock Asset Management

7.1. Overview

This cluster addresses both on-board (WP5 and WP6) and wayside (WP7) monitoring technologies for the design, testing and validation of intelligent rolling stock asset management solutions. Depending on the on-board or wayside element to be analysed, different technologies will be studied to obtain a correct prediction about the maintenance activities to be performed, resulting in an improved maintenance scheduled plan.
In addition, Telecommunication infrastructure used by Train Communication Network (TCN) to convey the train traffic, which is currently based on a wired system, will be greatly improved to enhance the functionality of both Train Control and Monitoring System (TCMS) and On-board Multimedia and Telematics (OMTS) domains.

A New Generation Train Communication Network (NG-TCN) has emerged as a major innovation of the European Railway industry, introducing a wireless architecture that replaces parts or the whole railway vehicles wires with wireless technologies. NG-TCN involves Wireless Train Backbone (WLTB) and Wireless Train Consist Network (WLCN) for inter-consist and intra-consist communications respectively, enabling innovative applications such as wireless virtual coupling and train platoons.

The activities performed in Cluster C are covered in WP5, WP6 and WP7.

The following Use Cases have been defined to meet the requirements to perform the demonstrators:

- UC 5.1: Bogie Monitoring System (on-board)
- UC 5.2: Health Monitoring & Analytics of HVAC & Brakes systems (ES)
- UC 5.3: Health Monitoring & Analytics and ML algorithms development of HVAC, Sanitary Systems & Brakes, Traction & auxiliary system (NL)
- UC 5.4: Health Monitoring & Analytics and ML algorithms development of Traction, HVAC, Doors, Batteries & Brakes (ES)
- UC 6.1: Development of next generation Traction control unit hardware and gate drive communication link
- UC 6.2: Traction Component Health Monitoring & predictive Maintenance
- UC 6.3: Set up of adaptive wireless telecom network between train elements
- UC 6.4: Adhesion estimation for management
- UC 6.5: Wayside signalling equipment monitoring system
- UC 6.6: On-board bogie diagnostic solution for fault detection applied to train(s) operating in Germany
- UC 6.7: Digital twin for energy
- UC 6.8: Smart maintenance scheduling tool
- UC 7.1: Bogie Monitoring System (wayside – acoustic, 2D-3D images, video and laser)
- UC 7.2: Pantograph Monitoring System (wayside – video and 2D-3D images)
- UC 7.3: General physical anomaly detection Monitoring System (wayside – video and 3D images)
- UC 7.4: Railway checkpoint use case (ES)
- UC 7.5: Railway checkpoint use case (NL)
- UC 7.6: Data path diagram use case
- UC 7.7: Data Analytics for Railway Checkpoints use case
- UC 7.8: Optimization of rolling stock maintenance use case
- UC 7.9: CBM algorithms for freight

A detailed description about Cluster C and its objectives, current status and KPIs can be found in **D2.6 Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue)**.

In addition, specific information about data exchange, including the type of data and its format is defined at **D6.1 User and functional specifications for multi-purpose resilient adaptative on-board telecom network and D7.1 Demonstrators Vision & Global Architecture for Checkpoints**.

7.2. Involved elements

In order to provide a general overview of the current situation and the involved systems in the demonstrators, the following systems can be found:

- Wayside-checkpoints: it covers every system that provides information related to the infrastructure and signalling system located in a correspondent checkpoint. This data is provided by different sensors that are involved in the infrastructure such as track circuits and catenary status, alarms and occupancies.

- On-board system: it provides with the information located on the rolling stock. This information is given through different sensors that are continuously providing the status of important parameters such as temperature, weight and vibrations.

- New external systems: these systems (which can be wayside or on-board) include the new technology to be used during the demonstrators. Currently, the technology level allows to use new sensors to measure different parameters that can be really useful for performing predictive maintenance activities.
  New sensors to be implemented are:

  - **Thermography technology**: infrared thermography is a passive imaging method for non-contact temperature measurement that creates a thermal map of the train surface identifying temperature anomalies.
  - **Line scan technology**: the line scan module acquires at high speed and high resolution, the upper surface of the contact shoe.
  - **3D technology**: the acquisition of the three-dimensional profile of the element, carried out by means of laser triangulation with high resolution cameras, can take up to 3.000 profiles per second.
  - **Acoustic technology**: the main technology consists of the analysis of sound radiation captured by microphone arrays which isolate the sound of individual elements as the train goes through.
  - **Vibration technology:** it is based on load bars and accelerometers to detect lack of roundness on wheelsets and determine damages on wheels or infrastructure.
  - **Train gauge technology**: the vehicle running gear condition and vehicle running behaviour - important inputs for vehicle maintenance - can be also monitored by measuring 3-dimensional wheel forces.
  - **Fiber optic sensors**: they are used for monitoring train integrity or derailing.
  - **Radiofrequency identification technology**: it is equipped with Radio Frequency Identification (RFID) and a reader to link and control each specific element such as train, fleet bogie or any other independent element.
  - **Image module technology**: this technology takes a colour picture of each element stored with the information coming from the other modules. It uses a standard colour area scan camera together with a proper infrared illuminating system.
  - **Laser-camera triangulation technology**: it determines the actual wear status and distribution. The processing system performs the analysis of the measured parameters and a comparison to define tolerance

thresholds.

- Data collecting system: it includes the virtual space in which the information previously explained is stored and modified to the correspondent format so that it can be used by the Machine Learning module. This is what we can find in this area:

    - **Importer logic**: this module is responsible for transforming data from previous technology to data that can be used by the Machine Learning module.
    - **Database**: its main function is to store the input data (already transformed) so that it can be sent to the Machine Learning module.

- Machine Learning system: this system is responsible for providing new solutions to the maintenance activities to be performed due to the Artificial Intelligence algorithms developed. These algorithms can receive, analyse and provide new information based on data previously obtained.
  By using Big Data Analytics, the system shall be able to provide predictive maintenance, increasing safety, reliability and efficiency of the operations.

- TMS: it is the final system, where the operators obtain the final results from the previous analysis. In this system, the initial scheduled plan can be compared with the new one provided by the new systems, taking the most optimal decision.

- Data exchange: data transfer between systems will be different depending on the systems to be connected. In general, systems will be connected through secure communication protocols, e.g. HTTPS and VPN, as well as versatile Data Formats like JSON or XML, and connected to the Cloud (and thereby to database and Machine Learning system) through an API.

- On-board telecom: Train Control and Monitoring System (TCMS) is an essential train subsystem for the functional onboard integration with other subsystems such as brakes, lights, doors, etc., whereas On-board Multimedia and Telematics (OMTS) conveys users and operator information.
  In order that all those subsystems can communicate with each other a Train Communication Network (TCN) is used general architecture in a hierarchical structure with two levels of networks, namely the Train Backbone Network (TBN) and the Consist Network (CN). TBN is responsible for the communications between the consists or what is referred to as inter-consist communications, whereas the CN establishes the communications in or among carriages that cannot be split apart during operation or what referred to as intra-consist communication.

- New Telecom Networks: the potential wireless technologies that might meet the requirements of NG-TCN in terms of data rate, latency, interference immunity and network dimension are LTE-V2X, Ultra-Wide band, Wi-Fi, ITS-G5, NR-V2X and Synchronous and Hybrid architecture.

Based on the elements explained before, figure 9 shows, at a high-level, the current architecture of the systems:

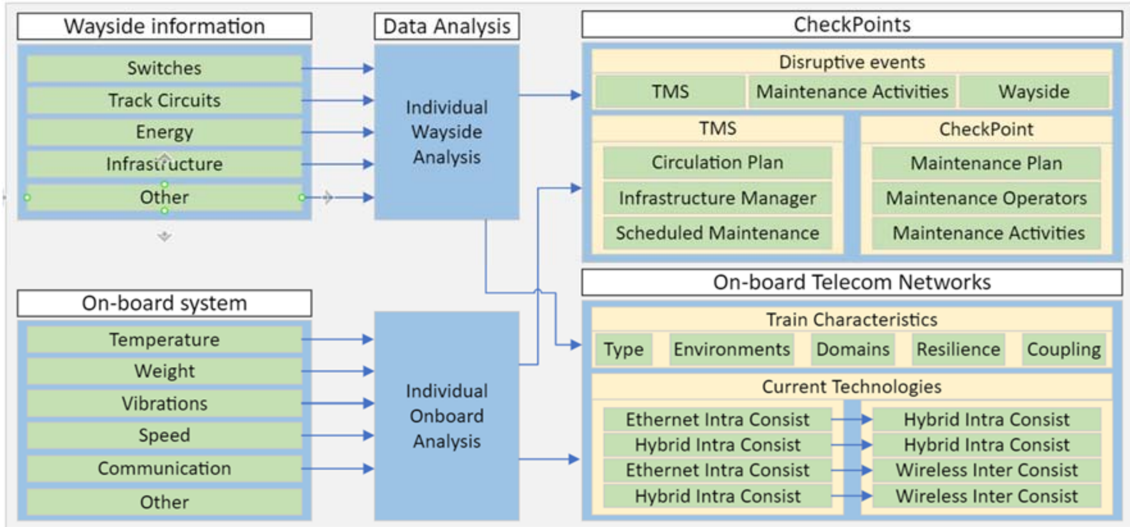

Figure 9. High-level system architecture for CheckPoints and On-board telecom networks.

7.3. Methodology

As it has been explained in previous paragraphs, there are two main topics in which Cluster C focuses. The first one consists of improving maintenance activities performed in Railway CheckPoints by employing new technologies such as IoT and Machine Learning. The second one focusses on improving the communication between the onboard system and the TMS, so that it is independent of physical elements. This would enable, as an example, Virtual Coupling (VC).

7.3.1. On-board Telecom. Networks

Overview

The methodology to follow for enhancing New Generation Train Communication Network (NG-TCN) focuses on replacing parts or the whole railway vehicles wires with wireless technologies. However, many challenges lie ahead in the NG-TCN migration, such as uncontrolled interferences from the coexistence onboard and at the station wireless systems. In addition, wireless channels are unstable and are prone to many random effects from the surrounding environment.

In order to solve these problems and succeed in the new communication system, it is necessary to follow the next steps:

- Define the user needs of the wireless TCMS system in order to identify the system requirements at both inter and intra-consist levels for all TCMS domains.

- Investigate the different possible scenarios of the new system implementation in order to set up the specifications for consist and backbone network.

- Perform literature research about the State of the Art to survey the candidate wireless technologies that could answer the system requirements such as LTE-V2X, UWB, ITS-G5 and NR-V2X. In addition to the technologies, a literature review of the different channel models for such a system in railway environment types, needs to be conducted.

- Analyse the coexistence of the system with other wireless technologies in the vicinity of the train such as the onboard passengers Wi-Fi, Wi-Fi at the stations, other systems such as Global System for Mobile Communications – Railway (GSM-R) and Future Railway Mobile Communication System (FRMCS).

- Performance analysis of candidate wireless technologies based on laboratory evaluation experiments and Matlab simulations. The different technologies will be compared in terms of metrics of interest, such as data rate, latency and propagation characteristics.

- Propose a possible robust, safe and versatile system architecture, that meets the system requirements and that is compatible with the railway constraints.

Architecture for Digital Coupling by new Telecom. Networks

The architecture for Digital Coupling by new Telecommunications Networks depends on the technology to be implemented. Thereby, the current architecture is not yet defined.

As the two coupling modes, mechanical and virtual, are completely different in terms of how consists are connected, different scenarios to those constraints need to be analysed in order to provide a secure wired-based communication to guarantee the safety of the passengers.

The train communication network consists of two sub networks, named intra-consist and inter-consist. **Intra-consist** network is composed of intra-carriage and inter-carriage networks**. Intra-carriage** consists of End Devices (ED) or/and Wireless End Devices (WED) that communicate with each other at carriage level using a switch or Wireless Access Point (WAP) respectively.

The inter-carriage network secures the communication among the carriages in a wired manner by using a consist switch (CS) or what it is referred to as Ethernet Consist Network (ECN), or in wireless manner using WAP. **Inter-consist** network acts at train backbone level, it performs inter-consist communication either wirelessly using Wireless Train Backbone Nodes (WLTBN), or via Ethernet Train Backbone Nodes (ETBN).

The current TCN is based on Ethernet at both intra-consist and inter-consist levels, to carry out the communications among trains and carriages as illustrated in figure 10.

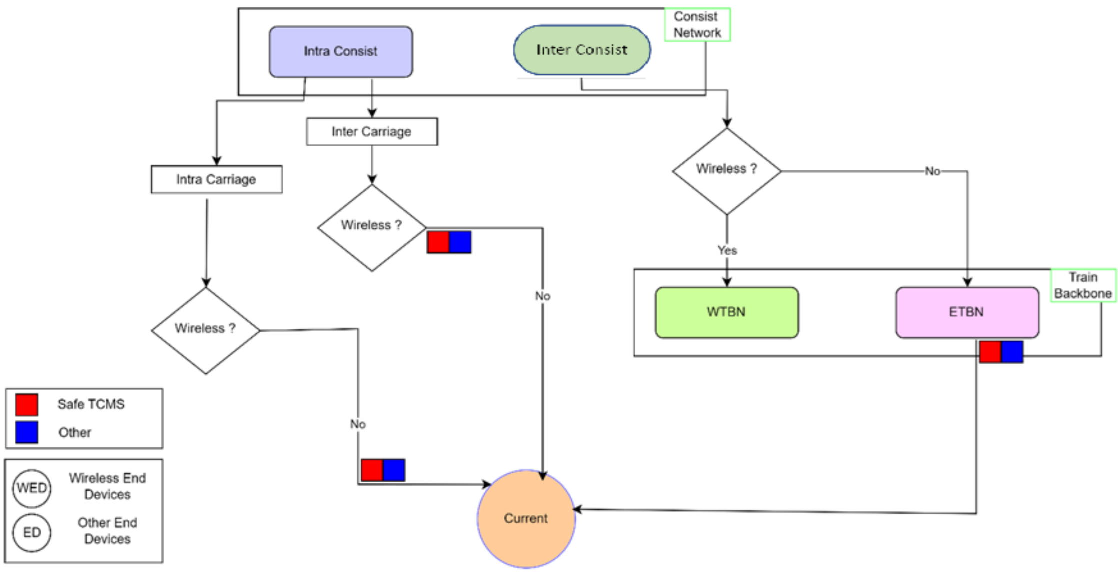

Figure 10. Current TCN usage diagram.

Different architecture schemes need to be defined in order to select the best option for New Generation Train Communication Network (NG-TCN). These possibilities are analysed and explained in detail at **D6.1 User and functional specifications for multi-purpose resilient adaptative on-board telecom network.**

7.3.2. Railway CheckPoints

Overview

The methodology to follow focuses on implementing existing Rolling Stock information in CheckPoints and new maintenance technology for detecting defects to improve maintenance activities in this area by using Machine Learning technology. Information provided by Rolling Stock (and Infrastructure) Assets as well as On-board information and data from TMS are critical elements to consider for succeeding at developing Machine Learning algorithms.

Once the algorithms are implemented, it is expected to experience a great improvement in maintenance activities performance, increasing capacity and knowledge at CheckPoints management.

Digging deeper into data analytics operation, Machine Learning and Big Data systems follow the figure 11 architecture:

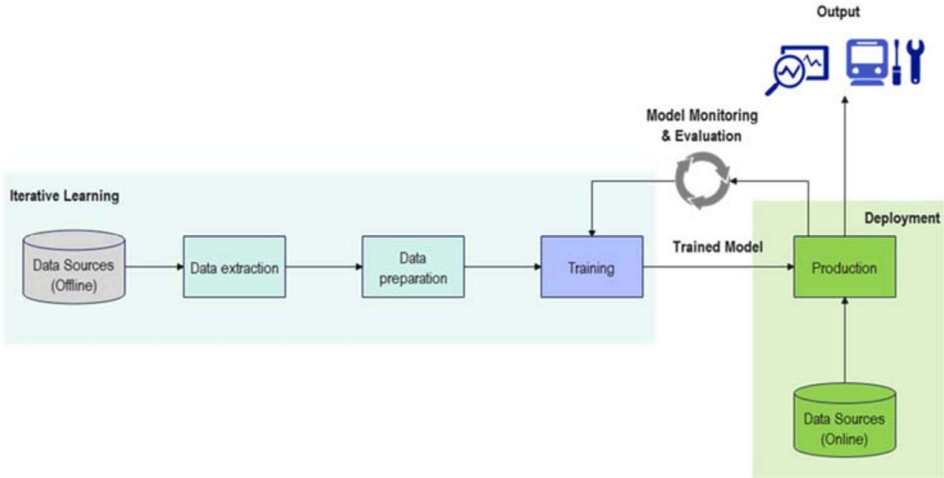

Figure 11. Machine Learning and Data Analytics architecture.

The following areas can be found:

- Iterative learning: it is the area where the algorithm training takes place. It includes the collection, storage and pre-processing of historic data sets based on previous activities. The more data sets are available, the better the results will be.

- Training: it is the most important part of the cycle. It receives input from historic data sets and, in real time, it also receives inputs from current data sources, which are analysed and transformed into the required outputs. It is important to highlight that it is necessary to perform an iterative model which considers new information and, in addition, keeps training the algorithm.

- Online data source: it is the input in real-time provided by current systems (Wayside and on-board information) and new technology systems thermography, vibrations…).

- Production environment: it is the final process, where the algorithm considers all information previously named and produces the result.

- Output: it is the result for the different maintenance activities. This output is stored in the cloud, where it is available for the Infrastructure Manager or the operator by connecting through the TMS.

New Architecture for Railway CheckPoints

By adapting figure 11 to Railway CheckPoints and using as data sources not only existing Wayside and On-board systems variables, but also the new technology variables explained in 7.2, the following architecture of the system can be concluded, being the new architecture to be deployed highlighted in green and blue.

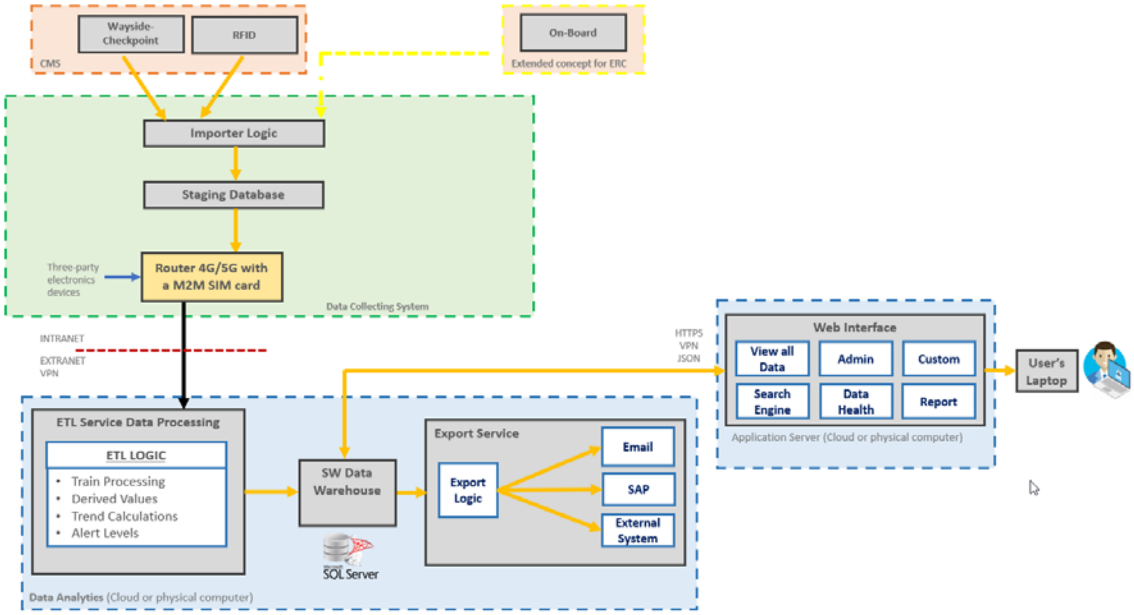

Figure 12. Architecture for checkpoints.

Where it can be found:

- Orange square: it includes the information provided by Wayside-checkpoints and from external systems (new sensors). This information, which is not modified, will be provided to Data Collecting System through the correspondent communication device.

- Yellow square: it includes On-board data. This information, which is not modified, will be provided to Data Collecting System through the correspondent communication device.

- Green square: it is part of the new technology use. In this space, data from On-board and the external systems is stored and modified in order to be adapted for the Machine Learning process. In addition, this area provides a communication channel to allow the connection with the cloud service environment.

- Blue square-1: it includes the cloud service environment. It is the virtual space where data is analysed and processed, and where the Machine Learning and Big Data Analytics are developed and deployed. Additionally, the cloud environment provides different possibilities for exporting data to the clients.

- Blue square-2: it includes the cloud client environment in the TMS. Due to online requests, the TMS can obtain, from the cloud service, the desired results and show them in different screens and formats, in order to compare the different maintenance activities for improving the scheduled plan.

Final result

As a result of the analysis performed during the previous sections, it can be concluded that cluster Railway CheckPoints focuses on improving maintenance activities not only by increasing the amount of available data by using new technology (IoT), but also with the analysis of the current available data and the use of Machine Learning models.
The implementation of these techniques and how they affect during operation will be a fundamental input to perform an optimised predictive maintenance plan and, therefore, an improved circulation plan.

The following figure shows an example of a sequential diagram between the schemes explained in the previous sections and what the data flow looks like in real-time operation:

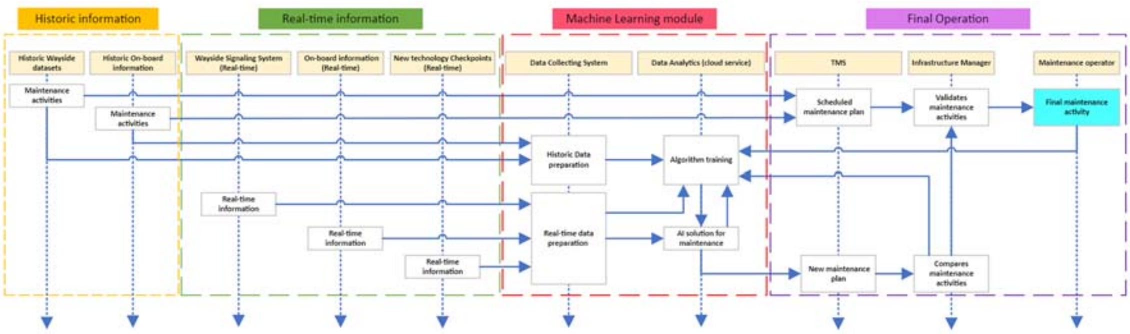

Figure 13. Sequence diagram for checkpoints.

8. Cluster D: Infrastructure Asset Management

8.1. Overview

This cluster addresses a great number of elements involved in railway systems as long-term maintenance and costs, track systems, innovative multi-purpose IAMS infrastructure applications and civil assets including structures, earthworks and geotechnics.

Focussing on the systems architecture, long term maintenance and costs are out of the scope of this document, and innovative multi-purpose IAMS infrastructure applications is completely related to TMS linking, which is explained in chapter 6. For this reason, this chapter focusses on explaining the architecture for data exchange involved in track systems and civil assets. The activities performed in Cluster D are covered in WP8, WP9, WP10, WP11, WP12 and WP13.

The following Use Cases have been defined to meet the requirements to perform the demonstrators:

- UC 8.1: Long term asset management and LCC
- UC 8.2: Holistic long term asset management
- UC 9.1: Sensing railway superstructure system components
- UC 9.2: Railway infrastructure monitoring using optic fiber
- UC 9.3: Track geometry and S&C condition monitoring
- UC 9.4: Infrastructure monitoring solutions
- UC 9.5: Prescriptive maintenance solutions
- UC 10.1: Linking (new) monitoring technologies to asset management issues
- UC 10.2: Fusion of (on-board and wayside) monitoring data for an enhanced fault detection and diagnosis
- UC 12.1: Multiscale monitoring of civil assets
- UC 12.2: Bridges and earthworks assets management aided by geotechnics
- UC 12.3: Monitoring of tunnel, sub-ballast layers, subsoil and predictive maintenance for tunnels
- UC 12.4: Data Analysis for condition monitoring

A detailed description about Cluster D and its objectives, current status and KPIs can be found in **D2.6 Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue)**.

In addition, specific information about data exchange, including the type of data and its format is defined at **D10.1 High-Level System Architecture.**

8.2. Involved elements

In order to provide with a general overview of the current situation and the involved systems in the demonstrators, the following can be found:

- Data Analytics Platform: this system is responsible for collecting, processing, and interpreting data related to various aspects of the rail infrastructure. It uses analytics tools and techniques as Machine Learning to identify trends, patterns, and insights from the data and involves generating reports, visualizations, and recommendations that aid in making informed decisions for optimizing rail operations.

- Decision Support System: it is a sub-system of the TMS which focusses on providing the different options for maintenance activities to the Infrastructure Manager, so that it is possible to choose the best possibility.

- New external systems: these systems (which can be wayside or on-board) include the new technology to be used during the demonstrators. Currently, the technology level allows to use new sensors to measure different parameters that can be really useful for performing predictive maintenance activities.

Some new sensors to be implemented are:

- **Intelligent sleeper**: New sleepers shall provide different data as temperature, flood detection, track settlements, landslides, loading conditions or vibrations, giving and effective automatic condition assessment and allowing to optimize maintenance activities decisions.

- **On-board LIDARS for Ballast**: this system focusses on designing estimation methods that convert cloud points from LIDAR into useful information about the ballast profiles and volumes. Based on visual conformity evaluation, the key parameters estimated are to be embedded into the decision support tools

- **Leonardo Platform**:
  - <u>Ground Penetrating Radar (GPR):</u> By including the use of 3D radar, the system can measure at a slightly greater depth than the air-coupled antennas (horn antennas) normally used, providing a higher resolution (measurement density) and revealing much more detail.
  - <u>Axle Box Accelerations (ABA):</u> this system allows to obtain data from track geometry in a cheaper way than currently track geometry measurement systems, allowing to monitor rail wheel contact.

- **Multi-Sensor wayside monitoring**: data generated by sensors and systems installed in the track and in the vicinity of switches and crossings, either raw or processed. Some examples of this data are inertial (accelerations, displacements, forces, etc.), electrical (e.g. currents and voltages), temperature, acoustic emission, etc. In addition, civil infrastructure monitoring assets are also included in the monitoring systems, such as bridges, hydrogeological assets, vegetation and tunnels.

- **Communication through optic fiber**: sensing based on optic fiber focuses on monitoring railway superstructure components and events for distributed sensing to the specific applications and their railway environments, such as train identification and intrusion detection. In addition, dark fiber solutions are developed for vibrations, damaged wheels, rock fallouts, and the integrity of trains and embankments.

Based on the elements explained above, Figure 14 shows, at a high level, the actual architecture of the systems. It should be noted that the systems will have their own data flow and detailed characteristics. Only a general outline of the common architecture is given below.

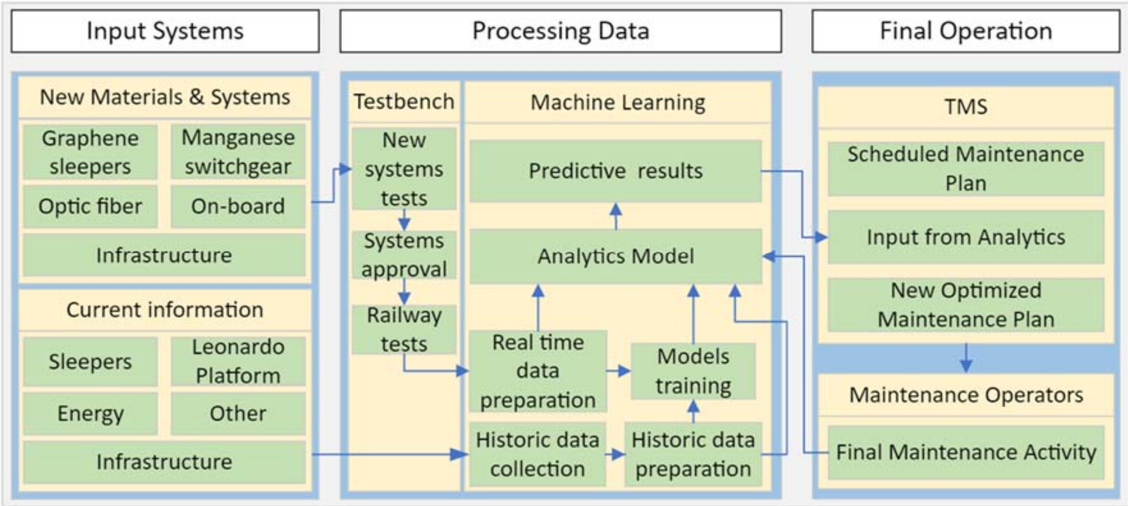

Figure 14. Mid-level architecture for Infrastructure Asset Management.

8.3. Methodology

The methodology to be followed includes not only the inclusion of new technology to obtain new data sources for improving maintenance activities such as intelligent sleepers or Leonardo platform, but also the improvement of existing technologies and the analysis, processing and results of the involved systems.

Although the use of new technology will follow a different flow to ensure its performance, both new technologies and new sensors that are already successful in other areas but are new to Rail will follow the same methodology, which can be summarised as analysing, processing and comparing results.

The main objective is to incorporate new materials (or new technology) into existing technology to improve the behaviour of components, thus obtaining better information about their condition and optimising maintenance activities, which implies a reduction of maintenance costs. First of all, a major analysis of current data is needed, not only on what data is available, but also on which elements need to be improved and how to improve them. These elements have been selected due to previous analysis performed to match their characteristics with the required capacities.

Some examples of the new elements are the use of graphene instead of concrete for improving the sleepers, the use of manganese as switch-heart or the magnetic microwire.

In addition, before including them in the railway network and for security and safety

reasons, these new materials need to be tested in a laboratory by using different applications of a testbench.
Once this analysis is performed, new technology application based on Machine Learning needs to be developed (or updated in some scenarios) to be able to process data both previously stored and available in historic records or coming from new systems.
Finally, it is necessary to define how the results are shown to the IM so that it is possible to take a decision with enough criteria.

The following figure shows an example of a sequential diagram between the schemes explained in the previous sections and what the data flow looks like in real-time operation:

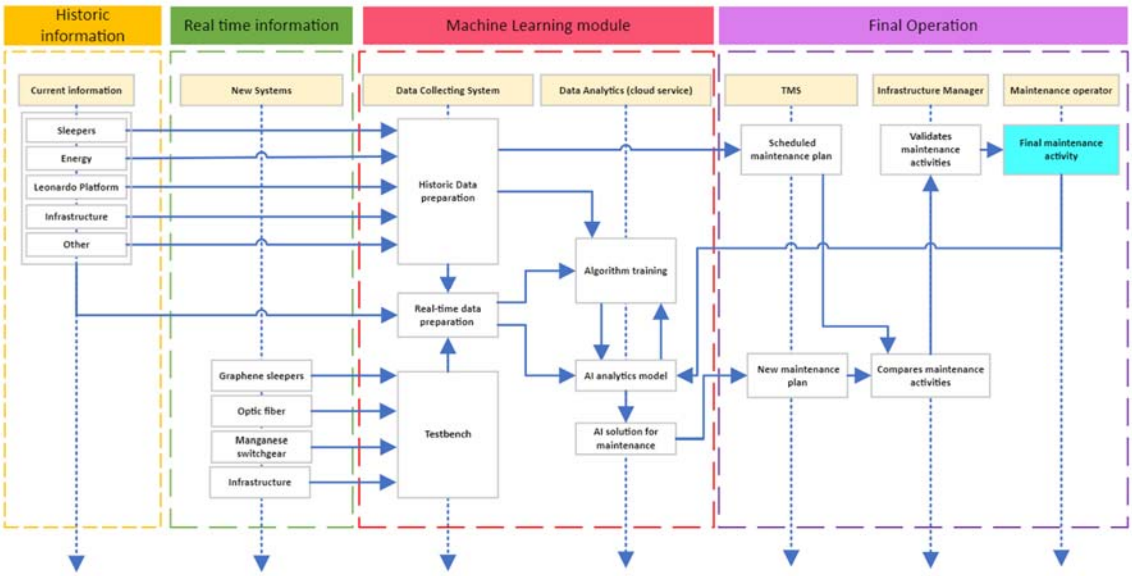

Figure 15. Sequenced diagram for Infrastructure Asset Management.

9. Cluster E Demonstrators: Railway Digital Twins

9.1. Overview

This cluster addresses the implementation of Digital Twins (DT) across the rail sector (WP14 and WP15) including improvements in decision support system, Virtual Certification, track visual inspection by unmanned means (drones) and BIM models.
Basically, a Digital Twin is a logical construct that incorporates data, models, algorithms, software, etc., that can be associated to a physical system and accompanies it.
In order to incorporate all this data, Cluster E aims to participate and collaborate in a repository hosted by al members in which each area needed by Decision Support System, Virtual Certification, Unmanned means visual inspection and BIM models are covered.

The activities performed in cluster E are covered in WP14 and WP15.

Thereby, DT needs to cover, at least, the following minimum requirements:

- The DT support environment is a repository of models that contain minimal physical model information and standardised interfaces. Consider, for example, a braking subsystem: it may require a braking demand as input, regardless of whether it comes from the driver or from an automatic control, and provides braking torques for each set of wheels as output. The minimal model may simply contain algebraic relationships between input and output or braking demand and torques, respectively.

- The DT design time environment uses these minimal models to design assemblies, but of course adopted for the railway field. In addition, exemplary algorithms and test data, for example, for analysis or prediction, are to be included.

- The DT runtime environment is a collection of environments where these models, algorithms and data are evaluated.

The following Use Cases have been defined to meet the requirements to perform the demonstrators:

- UC15.1: Decision support systems for railway station asset management
- UC15.2: Virtual Certification
- UC15.3: Demonstration of track visual inspection by unmanned means (drones)
- UC15.4: BIM model as support to communicate and populate the Station's Asset Management System

A detailed description about Cluster E and its objectives, current status and KPIs can be found in **D2.6 Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue)**.
In addition, specific information about data exchange, including the type of data and its format is defined at **D2.2 Definition of inputs for TMS specific Data Structure**.

9.2. Involved elements

In order to provide with a general overview of the current situation and the involved systems in the DT, the following elements can be found:

- Decision Support System (DSS): DSS are software platforms part of the TMS that provide tools and information to help station managers make informed decisions related to station operations. These systems use data analytics and modelling to help station managers analyse complex scenarios and make decisions that are optimised for operational efficiency, safety and passenger experience. Focussing on DT environment, the following capabilities need to be addressed:

- **Capacity planning tools**: used to optimise the use of station facilities and resources, such as platforms, ticketing systems and waiting areas.
- **Incident response systems**: provide real-time information on incidents that may occur at the station, such as accidents, security breaches or system failures. These systems use data from various sources, such as CCTV cameras, sensors and passenger feedback.
- **Predictive maintenance systems**: use data analytics and machine learning algorithms to predict equipment failures and schedule maintenance activities proactively.
- **Customer feedback analysis tools**: help station managers understand the passenger experience and identify areas for improvement.
- **Performance monitoring systems**: provide real-time information on station operations, such as train schedules, passenger flows and equipment performance.

- CCTV Cameras: intelligent analysis of videos collected by CCTV cameras are considered for improving railway station asset management system. The detection of rubbish, dirty surfaces, detection of overflowing bins, etc., will support the cleaning process and will allow to create a digital 'station model' that will provide a source of data for learning and testing of vision algorithms, including those based on deep neural networks. The digital model created will then be able to be used in other elements of the system - e.g., for highlighting maintenance issues.

- Data lake repository: it is the best solution for storing and analysing the data used to manage the station infrastructure. This information has completely different characteristics, coming from different sources and in different formats. Data lake repository allows to centralise the information, allowing to store and manage large volumes of structured, semi-structured and unstructured data at scale, making it more flexible for analysis.

- Virtual Certification: it runs a complete instance of the virtual certification process for specific assets, to introduce tracking, including the synergistic use of advanced asset inspection and data processing techniques, Digital Twin for data sharing, asset simulation to support compliance assurance and blockchain for process tracking and certification management. The certification process follows the next steps:

  - IM exposes data asset as foundation for its Digital Twin in a common data environment.
  - IM performs track survey, update and enriches the Digital Twin,

processes track status and triggers maintenance action.
  - The maintainer accesses asset data, plans and performs maintenance.
  - The maintainer updates and enriches the Digital Twin, requires verification of compliance.
  - The Validator accesses the asset data and performs the asset simulation as part of the full set of required verifications (which are outside the scope of the use case), issues the declaration of conformity.

- Automatic track visual inspection by unmanned means (drones): drones, with their ability to fly and capture high quality images, video footage, and data from LiDAR and other sensors, can offer a solution to determine the necessary nature of maintenance actions and their urgency by avoiding traditional visual inspections by field personnel. Algorithms for processing visual and other data need to be developed and trained to cross-check with existing infrastructure models and identify new suspect asset states.

- Building Information Modelling (BIM models): BIM is a collaborative process that involves creating and managing digital representations of the physical and functional characteristics of buildings and other physical assets throughout their lifecycle. To ensure the functionality of station building, the Infrastructure Manager needs information for decision-making and interventions.

  The availability of information is very important for the planning of maintenance interventions. By leveraging the comprehensive data-rich environment provided by BIM, asset management strategies can be implemented more effectively and efficiently. This integration allows for enhanced decision-making processes, improved asset maintenance and operation, reduced lifecycle costs and increased sustainability.

  The main objectives are to create a digital twin using BIM models to:
  - Have up-to-date building data "As-built", to reduce maintenance costs, reduce intervention times and increase user satisfaction.
  - Identify the process and information required in the BIM Model for asset management interventions.
  - Deploy a methodology for updating BIM information.
  - Identify the technology needed to develop a BIM-AIM working method and Digital Twin.
  - Respect a methodology for the exchange of information between the asset management system, the digital twin and the BIM Model.

- Predictive maintenance module: it is a new system that will collect all the data provided as input by the previous systems and provide suggestions for maintenance activities. In order to optimise each system, different models need to be developed and implemented.

Figure 16 shows the general architecture to be followed by DT environment.

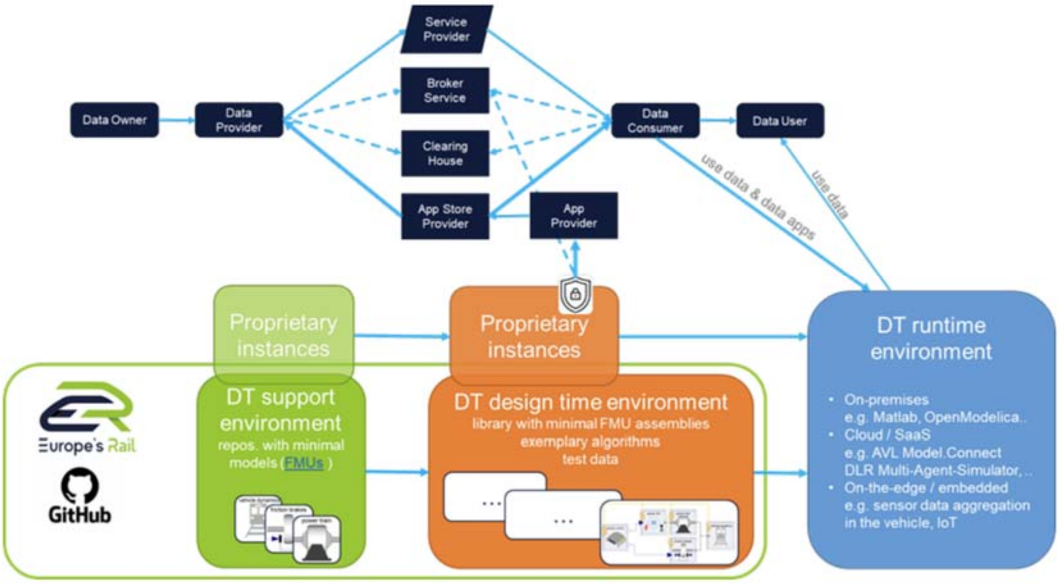

Figure 16. Digital Twin general schema in ERJU environment.

9.3. Methodology

The methodology to be followed focuses on analysing, collecting, classifying and using new data and existing data to create a virtual environment as close as possible to the real one, which involves not only the use of virtual technology to represent reality, but also includes the process of using Machine Learning technologies, which allow information to be automated and updated to achieve solutions that would otherwise be out of reach.

The following systems must be deployed to cover the requirements explained in chapter 9.2:

- Digital Twin: instead of having multiple systems for retrieving asset information, DT allows Infrastructure Managers using a unique environment to access all information related to the digitalised assets, explore asset locations inside the point cloud and display the track conditions in synchronisation. This will increase and support further digitalisation of the assets and support proper decision making as well as work scheduling.

- Track Substructure modelling and simulation: this system aims to model the behaviour of the substructure based on the different operational and track infrastructure conditions. This way, IMs can assess in advance how current conditions can evolve in the future and proactively respond and mitigate the risks. The simulated forces and how these are distributed to the substructure will act as an additional complementary and insightful data stream for the IMs to support objectively their maintenance decisions and explore the real root-cause of the events.

Both systems will be fed by available information provided by the data lake, in which initial systems are able to drop all required data. This data shall follow a process of analysis and preprocessing in order to adequate data to applications needs.
Thereby, the next steps need to be accomplished:

1. <u>Collect information:</u> it is the first step towards a successful simulation environment. The information to be used as input is the source of the data to be obtained. Type, format, periodicity, quantity and quality are some of the parameters to be considered. While some of this information must be obtained and modified from historical repositories, other information such as data obtained from new technologies or other simulation environments (e.g. new topologies or CCTV camera images) must be analysed to determine its usefulness.

2. <u>Analyse information</u>: once the information is obtained from input systems, data needs to be classified and processed. The proposed architecture includes a virtual environment that belongs to all members named "Data Lake". In this repository, the data must be modified so that it is ready to be used by Machine Learning and Digital Twins models.

3. <u>Use of data:</u> after processing data, there are different options:

    a. **Data is used by Machine Learning models**: by training and developing the models, the results will be used to provide optimised solutions for the different systems.
    b. **Data is used by Digital Twin**: by using available data, DT can create a virtual environment similar to the real one.
    DT thereby shall have tools that allow to simulate different options for an activity, so that it is possible to compare and select the best solution. In addition, by connecting Real-time data to DT, it is possible to obtain updated information (from the BIM tool, for example) about the activities carried at any moment, comparing it with the simulations and selecting the best solution.
    c. **Data is used by Building Information Modelling**: by using available data, the BIM tool can create a representation of a station. Using as input not only raw data but also processed data from Machine Learning techniques, it is possible to detect issues and shorten the time to solve them. In a similar way as DT, BIM can be connected to Real-time systems

so that updated information is available.

d. **Data is used by Virtual Certification**: as explained in chapter 9.2, virtual certification faces several issues at obtaining all required data from different sources. In addition, this information is usually incomplete or cannot be found. By using Data lake repository, information needed must be located and updated, improving thereby the Virtual Certification Process.

The following figure shows the proposed architecture for DT and BIM environment.

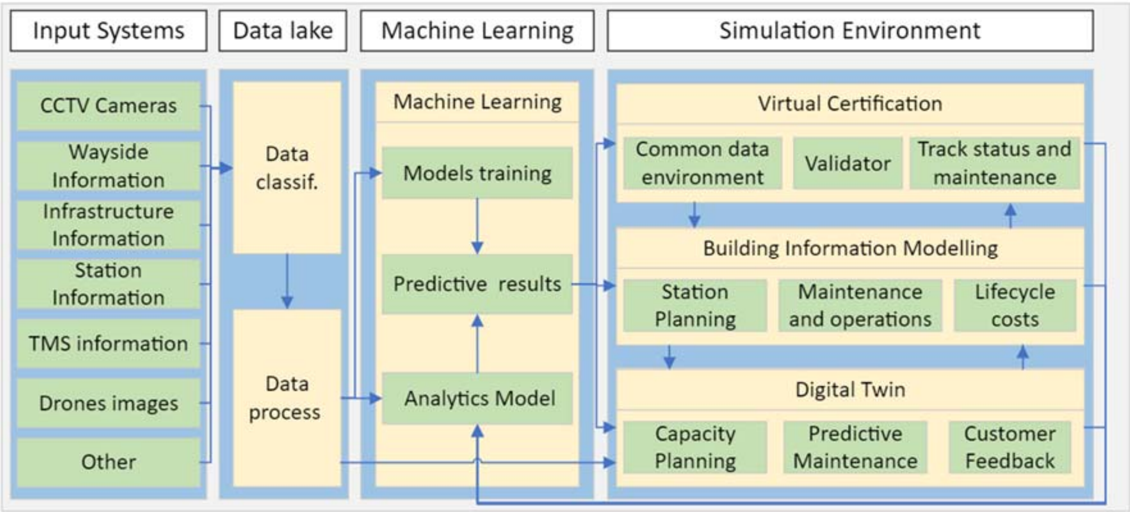

Figure 17. Mid-term architecture for DT and BIM models.

10. Cluster F: Environment, User and Worker Friendly Railway Assets

10.1. Overview

Cluster F has the objective of creating environment, user and worker friendly railway assets addressing environmental and cost-effective lines (WP16), new additive manufacturing repair processes (WP17), robotic platforms for railway interventions (WP18) and Augmented Reality, as well as exoskeletons, to support railway maintenance (WP19). Optimisation of design solutions, production and maintenance of the railway could significantly reduce the environmental impact in production and operation.

Thereby, Cluster F focuses on two main topics for the improvement of railway infrastructure:

- <u>Use of new materials to improve railway lines characteristics</u>: by optimising the design of solutions, production and maintenance can be upgraded. The use of new technology as additive manufacturing (AM) and digital warehouse (DW) can significantly reduce environmental impact as well as increase the availability of the track. The study of ballast destruction, squats in rail, dynamic effects on bridges and metallic elements deformations are some of the key objectives of this topic to be improved.

- Maintenance automation: by automating systems for wayside inspections by using new technology such as light and flexible on track inspections, automatic installation of ERTMS balises and axle counters, railway maintenance robots or the use of augmented reality tools, it is expected to optimise railway maintenance by reducing the number and costs of interventions.

The following Use Cases have been defined to meet the requirements to perform the demonstrators:

- UC16.1: Green tracks and turnouts.
- UC16.2: Resilient and sustainable lines.
- UC17.1: In-situ AM repair machine for rails, switches and crossings.
- UC17.2: AM repair machine for wheels.
- UC17.3: In-situ repair of track metallic assets.
- UC17.4: Stationary solution for AM repaired turnout crossings using WAAM technology.
- UC17.5: Additive Manufacturing of large interior flame-retardant polymer spare part.
- UC17.6: Digital warehouse.
- UC18.1: Light and flexible on-track inspection.
- UC18.2: Automated installation of ERTMS balises and axle counters.
- UC18.3: Disinfection of trains and small stations.
- UC18.4: Train underbody inspection.
- UC18.5: Automated fixed crossing repair.
- UC18.6: Purchasing railway maintenance robots.
- UC19.1: Upper-body exoskeleton for worker's support in railway industry.
- UC19.2: Augmented Reality tools to help and guide railway workers in maintenance operations.

A detailed description about Cluster F and its objectives, current status and KPIs can be found in **D2.6 Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue)**.

In addition, specific information about data exchange, including the type of data and its format is defined at **D16.1 Scientific methods descriptions for sustainable and cost-efficient eco-design for rail assets demonstrators and D18.1 Common Framework Orientations**.

10.2. Involved elements

In order to provide with a general overview of the current situation and the involved systems in the Cluster F, the following elements can be found:

- New materials analysis: it includes the analysis, test and use of new materials in order to improve the railway transportation by reducing environmental impact and maintenance activities while ensuring safety and capacity. These new materials focus on wayside infrastructure as well as the technology to be employed to measure their status and can be highlighted:

    - **Free balise system for track and turnouts**: the settlement processes occurring with conventional turnout systems are very unequal regarding their special distribution which makes turnouts especially prone to need maintenance in form of tamping or a change of their ballast bed before the estimated product lifetime has ended. The proposed solution is an optimised track/balise system with adjusted fastening systems, where the protection of the ballast is a focus point.
    - **Squat resistant reduction**: the repair of squat defects causes high efforts in workloads which needs to be detected and estimated early to minimise maintenance cost and increase reliability in the railway. Through the analysis and testing of the squat ladder, new material compositions for track rails and turnouts are intended to be obtained.
    - **Emission free turnout heating system**: the objective under study is to maintain the serviceability of infrastructure assets in adverse situations, such as during cold weather conditions, by ensuring the free movement of all moving parts of a turnout through the use of geothermal turnout heating.
    - **Dynamic effects on bridges analysis**: by using bridge dynamics resonances, Scour-flood tools and geogrids for track bed reinforcement, the main objective is to obtain a predictive approach to assess the flood risk to develop train-track-bridge interaction models for realistic estimation of dynamic effects on bridges.

- Additive Manufacturing: by adding material instead of replacing it, it is possible to achieve the same dimensional and functional characteristics for the involved elements before the fault, so that an important cost saving maintaining operational capacity of the systems is possible. The following elements are in the scope of additive manufacturing:

    - **Repair machine for rails, switches and crossings**: machines integrate several subsystems to remove material before the repair, add material using Laser-DED powder, remove material to reach final dimensions and measure final dimensions. This method consists of depositing filler steel to form an electric arc between the supplying fuse element and the rail to be repaired, followed by subsequent grinding.

- **Repair of track metallic assets**: this conventional welding technology, assisted by other tools such as grinders, allows the rail components such as rails and switches to be recovered quickly.
- **Repair of turnout crossings using WAAM technology**: the development of a functional WAAM repair welding process for crossings and the use of specific material concepts will allow to affect the LCC in a positive way.
- **Large & flame-retardant polymer spare parts**: by using new materials, the objective is to print specific 3D components so that the characteristic of the restored element is satisfactory.
- **Digital warehouse**: the Digital Warehouse focuses on methods and technologies railway operators can use to procure or manufacture spare parts on-demand.

- Automation processes: by automating repetitive and manual processes, it is possible to increase efficiency and avoid human errors. The following systems are on the scope:

  - **Inspections and installation**: by automating and improving the inspection and installation systems, it is a fact that more accurate data will be available and, thereby, better decisions will be taken. In addition, by automating the installation of the systems, the workload of the operators involved is expected to be reduced. The following systems are analysed to be automated under Cluster F scope:
    - Light and flexible on-track inspection.
    - Train underbody inspection.
    - Automated installation of ERTMS balises and axle counters.
    - Augmented Reality tools.

  - **Railway maintenance robots:** the use of robots is essential to decrease the time and costs of maintenance activities. Cluster F aims to provide different attempts based on robots to support worker´s activities. The following cases need to be highlighted:
    - Automated fixed crossing repair.
    - Upper-body exoskeleton for worker’s support.

10.3. Methodology

The methodology to be followed distinguishes between the two main activities to be performed in cluster F.

On the one hand, the first focuses on the use of new materials and technology to improve maintenance activities. These new materials and processes must be tested in a laboratory environment to ensure that all the characteristics of the elements involved are successfully achieved while maintaining safety and security requirements.

Furthermore, the steps to be followed include not only the analysis of the new materials and how they behave in a laboratory environment, but also a phase in which the results are compared with existing ones and, if successful, the inclusion of these materials in real railway elements.

Finally, the last step for the new materials is to compare the maintenance performance of the new elements (such as reduction of squat resistance or repair of metallic track assets by additive manufacturing) with the current performance, so that characteristics such as deformation, temperature or vibrations can be measured and conclusions drawn.

On the other hand, the second activity that Cluster E performs focuses on automating processes to obtain and perform maintenance activities both in rolling stock and in wayside elements. To achieve this objective, new data collection systems such as the use of light and flexible on-track inspection or the automated installation of ERTMS balises and axle counters are used in different demonstrators, in order to compare the current manual systems with the automated ones.

After performing this data collection, it is necessary to compare the current data collection methodology with the new one, in order to measure different factors such as accuracy, quantity and quality of the data.

In addition, automation of processes also includes a sub-group of activities that covers:

- The use of Upper-body exoskeleton for worker’s support, especially during the execution of the most physically demanding maintenance tasks of the railway infrastructure. The steps that cover these activities can be summarised as follows:
    - To identify the most physical activities.
    - To analyse the possibility of performing these activities by means of robots.
    - To perform the maintenance activities with robots.
    - To compare results (quality, time and costs).

- The use of Augmented Reality tools to help and guide railway workers in maintenance operations, with the aim of providing railway maintenance workers with assistance during the assembly/maintenance procedures, reducing time and cost of these operations. The steps that cover these activities can be summarised as follows:
    - To identify the elements to be develop in Augmented Reality.
    - To develop the chosen elements.
    - To perform maintenance activities by using Augmented Reality to support these activities.

o To analyse and compare the results.

The following figure shows the proposed high-level architecture for improving maintenance activities:

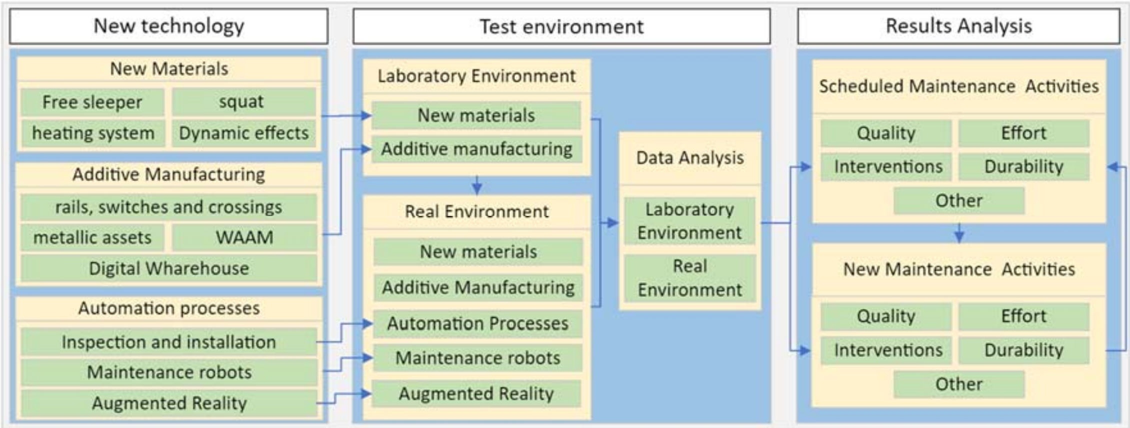

Figure 18. Cluster F high-level architecture.

11. Conclusion

The goal of this document is to provide an approach of the high-level architecture of the different Clusters of FP3-IAM4RAIL.

Although the clusters allow to identify and classify the involved elements and actors depending on the area they belong to in railway management, each cluster includes a great number of interrelated elements involving other areas. This implies that the architecture schemes only provide a summarised idea about what it is wanted to be developed, which is likely to change as the various demonstrators evolve.

As the architecture for each demonstrator is likely to change, this document focuses on providing a general description of the involved elements and the different processes that most of the demonstrators shall follow in order to achieve their expected results. This initial architecture can be summarised in the following sections:

- Input elements: it includes all data needed as initial input for the prototypes. Depending on the goal to be reached, different data as historic, real-time or new data may be needed.
- Analysis of data: after obtaining the data, a phase for analysing and transforming data is necessary in most of the demonstrators. This phase also includes the development of technology systems as can be e.g. Machine Learning modules.
- Test phase: it includes the data processing and the activities performance in both the laboratory and in a real environment.

- Results analysis: it is the final step, where the results from the different demonstrators are analysed. This phase not only includes how the maintenance plan could change, but also how the new materials, activities or new systems can affect in terms of quantity, quality, safety or costs.

However, a deeper analysis of the architecture needs to be performed to completely describe the data flow, methodology and expected results in each specific demonstrator.

The final architecture will be completely described at **D2.3 Architecture Requirements Consolidation final version**, where specific data, systems and expected results will be explained in detail.

12. References

FP1–MOTIONAL – Deliverable D26.1_Process to collection of use cases and establishing cooperation with all Destinations and System Pillar

FP1–MOTIONAL – Deliverable D28.1_Summary on other Destinations Digital Twin use cases

FP3–IAM4RAIL – Deliverable D2.6_Definition of Use Cases, including Innovation, Business Assessment, KPIs definition and roadmap (first Issue)

FP3–IAM4RAIL – Deliverable D2.2_Definition of inputs for TMS specific Data Structure

FP3–IAM4RAIL – Deliverable D3.1_IAMS Vision, Validation & Architecture Report

FP3–IAM4RAIL – Deliverable D6.1_User and functional specifications for multi-purpose resilient adaptative on-board telecom network

FP3–IAM4RAIL – Deliverable D7.1_Demonstrators Vision & Global Architecture for Checkpoints.

FP3–IAM4RAIL – Deliverable D10.1_High-Level System Architecture

FP3–IAM4RAIL – Deliverable D16.1_Scientific methods descriptions for sustainable and cost-efficient eco-design for rail assets demonstrators

FP3–IAM4RAIL – Deliverable D18.1_Common Framework Orientations

FP5–TRANS4M-R – Deliverable D25.3_Report on the basic functional and technical specifications regarding CMS as relevant input for FP3